

On the Development of Laboratory Projects in Modern Engineering Education

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Abstract—Whilst a solid theoretical foundation is important in any undergraduate engineering program, practical exercises and educational laboratories play an equally vital role in educating knowledgeable and skillful engineers that can immediately enter the industry without requiring extensive practical training. However, with the ongoing rapid advancements in technology, a constant challenge faced by educators is the need to design new and relevant laboratory projects. This can be a time-consuming and costly affair, which, if neglected, will lead to outdated laboratory projects and a degradation in learning outcomes for the students. Here, we present an approach that can overcome this challenge by means of low-cost modern equipment and supervised student labor, exemplified by the development of three different laboratory projects designed for electrical engineering students.

Index Terms—modern engineering education, laboratory projects, low-cost equipment, student labor, learning through construction.

I. INTRODUCTION

The technological revolution is proceeding perhaps more rapidly than ever observed before. Terms such as the Internet of Things (IoT), Industry 4.0, cyber-physical systems, artificial intelligence, machine learning, and autonomous systems have become commonplace in a world of electrification, digitalization, and automation. For undergraduate engineering programs to remain relevant, course curricula must be updated and new laboratory projects designed. There are scarce resources for teachers to keep on top of new technology, not to mention adopting new hardware in educational labs. Exploring new technology and designing new laboratory projects and experiments is a daunting task for the average teacher, who likely would need several semesters of time to complete such as task squeezed in between other duties. An alternative is to outsource the job to external professionals or pay internal teachers for extra hours outside of their ordinary position but this is very costly. Dedicated laboratory engineers can to some extent mitigate the situation but their work demands are often similar to those of teachers because laboratory engineers must serve numerous teachers and courses simultaneously.

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In the automation engineering program at our university, we have recently investigated the possibility of engaging students during the two-month summer break for developing new laboratory projects for our courses. Students are very appreciative of this opportunity, where they get to learn a lot about new technology whilst earning income (about 160 NOK/hour, corresponding to about 19 USD/hour) at the same time. Projects are usually dimensioned to take about 120 or 240 hours to complete, with one or two students working on each project. The remaining cost relates to the equipment, which is the same no matter who develops the laboratory projects, supervision of the students, and final polish and preparation for adopting the projects in courses. To cover the cost of hiring students, we have obtained funding through a university centre for excellent IT education, [NTNU Excited](#), which reduces the cost further. Admittedly, such arrangements do not exist in all institutions. Nevertheless, even without such funding schemes, we deem our approach as very attractive when compared to the alternatives mentioned above.

An important advantage of engaging students for developing new laboratory projects is gaining insight into the student perspective. Experienced teachers can easily avoid the most common pitfalls faced by students but sometimes it is hard for teachers to really understand what students find difficult. Thoroughly documenting their work, the experiences of students in the development phase can be used pedagogically by teachers when designing laboratory projects carefully aligned with intended learning outcomes. Moreover, the students can subsequently be hired as student assistants and laboratory demonstrators when the laboratory projects are adopted in engineering classes. The students are grateful for the opportunity of a part-time job and learn a lot from helping fellow students in the lab, whilst the teacher's workload can be reduced and supplemented by students with first-hand experience with the projects.

In the following, we first present a historical overview of theory-driven, practice-driven, and technology-driven approaches in engineering education, with an emphasis on laboratory instruction, before presenting some relevant learning paradigms (Section II). Next, we summarize three example laboratory projects that were run during the summers of

2017 and 2018 (Section III). The projects are relevant across several engineering disciplines but in particular for electrical engineering programs. Finally, we discuss the advantages and challenges of our approach and draw some connections to the literature, as well as point to possible future work and make some concluding remarks (Section IV).

II. LITERATURE REVIEW

In the following, we provide an overview of the historical role of educational laboratory practice in engineering education, present major shifts in engineering education with an emphasis on current and future trends, and present some key learning paradigms.

A. Historical Role of Laboratory in Engineering Education

Engineering is a practical discipline concerned with applying scientific theory and methods for solving real-world problems. Consequently, instructional laboratories have always played an essential part of engineering education in the USA and in Europe, although to a varying degree.

1) *USA*: In a seminal paper by Lyle D. Feisel and Albert J. Rosa about the role of laboratory in undergraduate engineering education [1], the authors provide a historical overview dating back to the early 1800s with a focus on engineering education in the USA. During the nineteenth century, with the Industrial Revolution as an important driver, engineering education was predominantly practical, with an emphasis on laboratory instruction [1]. Subsequently, the engineering accreditation process that started with the the American Institute of Chemical Engineers around 1925 and the Engineers' Council for Professional Development (ECPD) in 1932, led to more emphasis on theory than practice, with laboratory practice being understated and more of an implicit part of engineering education [2].

This tendency was furthered fuelled by the fact the many of the technological advances made during World War II was invented by scientists, not engineers, which led the American Society for Engineering Education (ASEE) through its Grinter report in 1955 [3] to conclude that existing engineering programs were too practically oriented and to recommend a strengthening of the basic sciences (maths, physics, chemistry).

In addition, the 1970s experienced a cutback of funding for technology and engineering education in the USA in the aftermath of the costly Moon landing and Vietnam war, which forced institutions to minimize their use of laboratory instruction [1].

Despite this shift towards more theoretical engineering programs, the industry was in continuous demand of engineering graduates with practical skills [1], and when the ECPD was reorganized as the Accreditation Board for Engineering and Technology (ABET) around 1980, emphasis began shifting towards better practical skills through laboratory instruction, culminating with the ABET Engineering Criteria 2000 (EC2000) at the turn of the millennium [4].

With the new engineering criteria, focus changed substantially from from a prescriptive, curricular-based standard to an outcomes-based approach for accreditation [5], and six new “professional” skills were introduced, including communication, teamwork, and understanding ethics and professionalism [6], which at least indirectly are related to laboratory practice. The ABET EC2000 engineering criteria, in revised forms, has continued to have a big influence on engineering education, also globally, with more than 4000 programs at nearly 800 institutions in 32 countries being accredited by ABET as of December 2018 [7].

2) *Europe*: The early history of engineering education (1750–1930) in Europe (and contrasted with the USA) is well covered in a much-cited paper by Peter Lundgreen [8]. In the period before 1870, the author argues that highly bureaucratized states like France or Germany had more academic and theoretical engineering education in contrast with England and the USA having a more practice-driven focus from industrial demands. The author then observes an international convergence in the years from 1870 to 1930, with trends as described for the USA in the previous section.

In a chapter on historical tensions in engineering education from a European perspective from about 1750 until today, Andrew Jamison and Matthias Heymann draw attention to the reasons behind educational approaches being theory-driven, practice-driven, or technology-driven [9]. In line with Lundgreen [8], they point out that France and southern European countries in early days (before early 1900s) were characterized by “book learning” and largely theory-driven engineering education, whereas England emphasized a practice-driven approach and “learning by doing.” Germany, and the Scandinavian countries, on the other hand, established both scientific and technological universities in the nineteenth century, embracing a hybrid, or technology-driven approach, institutionalized in the form of laboratory-based learning being a major component in the education process [9]. Subsequently, during the twentieth century, technical universities increasingly adapted to scientific and technological change and growth of knowledge through differentiation of education [9], most prominently exemplified by the Bologna Process and the Bologna declaration that was signed by education ministers from 29 European countries in 1999.

Today, the Bologna Process is an intergovernmental cooperation of 48 European countries in the field of higher education [10]. It has led to a European standardization of degree programs and a differentiation in education in which vocational schools typically offer 1–2 year technician degrees, and universities and colleges typically offer 3-year bachelor degrees and 3-plus-2 or 5-year master degrees, in engineering. The role of laboratory and practice-driven engineering education is important across both the vocational, bachelor, and master level but obviously, the emphasis on a scientific and theoretical approach for solving engineering problems increases with higher degree programs.

B. Modern Engineering Education

In a seminal paper by Jeffrey E. Froyd and colleagues [11], the authors identify five major shifts in engineering education since early 1900s till today: (1) a shift from hands-on and practical emphasis to engineering science and analytical emphasis (circa 1935–1965, with the Grinter report [3] playing an important role); (2) a shift to outcomes-based education and accreditation (circa 1990–2000, with ABET and EC2000 playing an important role [4], [5]); (3) a shift to emphasizing engineering design; (4) a shift to applying education, learning, and social-behavioral sciences research; and (5) a shift to integrating information, computational, and communications technology in education. According to the authors, the first two shifts have already occurred but continue to have implications for engineering education, whereas the latter three are still in process and their influences on practice are difficult to forecast [11].

The third shift has led to many engineering programs adopting a capstone design course, often with design playing an important role in the final-year thesis project, or a first-year or cornerstone design course, as part of the degree curriculum. Unfortunately, there is often a gulf between the engineering design experience in the first year and the capstone culminating design experience [11]. In a review of first-year design education in Canada and the USA [12], the authors strikingly observe that methods of instruction are remarkably uniform between universities, whereas the engineering design instruction methods widely differ, and suggest that at least in part, this variation is due to different resource constraints and priorities at universities. The most appropriate means to deal with this gulf according to a multiyear study by the Carnegie Foundation for the Advancement of Teaching [13] is to introduce a thick “spine” spanning all years of the engineering curriculum that ensures students experience and reflect on the demands of professional practice, bridging theory and practice.

The fourth shift relates to the influences of research in education, learning, and social-behavioral sciences, which are continuing to evolve [14]. According to [11], behavioral psychology has led to concepts such as learning objectives or learning outcomes, formative and summative assessment, and mastery model research outcomes and objectives becoming integral parts of the ABET Engineering Criteria and engineering accreditation in general (see the review by John Heywood for an extraordinary synthesis of nearly 2,000 articles to help make engineers better educators [15]). Moreover, social psychology research has led to approaches to teaching that increase student engagement, active learning, interactive learning, and especially cooperative learning, as well as learning communities and communities of practice [11]. Furthermore, cognitive psychology, education, and the learning sciences have led to inquiry-based learning methods including problem-based and project-based learning, approaches to promote conceptual understanding, and integrated course design [11].

The fifth shift, in which information, computational, and

communications technology are integrated in education, is the most futuristic one, and most difficult to predict. Froyd and colleagues list the following principal instructional technologies and their applications [11] but the list is not exhaustive: (i) content delivery: television, videotape, and the Internet; (ii) programmed instruction: individualized student feedback; (iii) personal response systems (“clickers”); (iv) computational technologies; (v) intelligent tutors: second phase of individualized student feedback; (vi) simulations; (vii) games and competitions; (viii) remote laboratories; and (ix) grading. At our institution, we have experimented with these technologies and applications in several of our courses [16]–[22]. In the following, we will provide an overview of the learning paradigms we deem most relevant for the engineering programs in which we teach.

C. Key Learning Paradigms

Below, we present some of the learning paradigms that most highly affect us in our own teaching.

1) *Active Learning*: Despite the emphasis on combining both theory and practice in engineering education, higher education is still dominated by the transmission method of teaching, which can be popularly rephrased as teaching by telling [23]. In a synthesis of research on the effectiveness of traditional lectures, Bligh [24] found that these are not very effective for personal development, skills or values, all of which are natural learning goals in higher education. Instead, there are several metastudies that show that active learning in science, technology, engineering, and mathematics (STEM) has several advantages regarding performance, ability to reproduce material, and motivation and engagement [25]–[27]. In particular, cooperative learning strategies have been shown to be particularly effective for achieving deep learning [28]–[31].

Several active learning paradigms can be identified [32], for example constructivism and collaborative learning, which originate from the theory of cognitive conflict by Piaget [33]; cooperative learning, based on the theory of Vygotsky [34] on the zone of proximal development; peer-assisted learning, defined by Topping and Ehly [35] as “the acquisition of knowledge and skill through active helping and supporting among status equals or matched companions” and thus encompassing both the theoretical positions of constructivism and cooperative learning; and peer-tutoring [36]. Another active learning method is problem-based learning, which has overlap with learning methods related to peer-assisted learning but importantly, problem-based learning can also be undertaken individually [32].

Educational laboratories obviously encompass many of the active learning paradigms listed above. Additionally, careful design of laboratory experiments and the problems to be solved is needed. One such tool that can help the teacher in the laboratory design process is constructive alignment.

2) *Constructive Alignment*: There has been a dramatic change in higher education worldwide for the last decades,

with more students enrolling, from a wider diversity of background, and with a broader range of approaches to learning [37]. At our own department, about 50% of our students have a background from vocational school [17]. Often, these students have strong practical skills and good self-discipline, for example due to work experience but it also means that their academic skills are sometimes lacking.

Engineering students of today conceive learning in several ways, including simple memorization of definitions, applying equations and procedures, or understanding physical concepts and procedures, as well as seeing phenomena in the world in a new way or changing as a person [38]. This taxonomy has a big variation among students, ranging from surface learning (memorisation) to deep learning (understanding and ultimately changing as a person). Additionally, a third category called strategic learning can be defined, in which students aim for good grades with minimal effort [39]. These conceptions of learning among students has necessarily had an impact on how higher education is being taught today [40].

Moreover, students' approaches to learning has a significant effect on achieving learning outcomes [41], [42], and hence, many studies have tried to identify factors that promote deep learning [43], [44], with a popular approach being the theory of constructive alignment (CA) [45]. CA merges (a) a constructivist view that students learn by doing, with (b) aligning the teacher, the students, the teaching context, the learning activities, and the learning outcomes [37]. Of particular importance is the process of backwards course design, first starting with the intended learning outcomes (ILOs), then defining assessment tasks closely related to the ILOs, and finally choosing teaching methods and learning activities aligned with the ILOs and assessment tasks [37].

3) *The Teacher as a Facilitator for Learning*: For successful implementation of CA, the teacher must be able to create a learning environment that facilitates learning activities that in turn make students achieve the desired learning outcomes [46]. However, even if teaching and learning components (such as the curriculum and the ILOs), the teaching methods, and the assessment tasks are aligned to each other, it is commonly accepted that self-monitoring and self-regulation (e.g., the ability to select and structure the material to be learnt) will highly affect the learning outcomes [47]. A lack of self-monitoring and self-regulation among students will lead to poor academic results [48], [49].

Gynnild [50] suggests that the teacher must adopt a role as a facilitator for learning, much similar to a personal trainer at the gym, guiding the trainee to do the right exercises, the right amount and level of difficulty, and encouraging and supporting the trainee, eventually making the trainee self-monitored and self-regulated. We have previously documented our attempts at adopting this role as a teacher by using the flipped classroom teaching approach [16], [18], but in traditional engineering courses (not using flipped classroom) that require a large portion of laboratory practice, this is equally important.

III. THREE EXAMPLE PROJECTS

In this section, we present three laboratory projects that were successfully implemented by students during the summers of 2017 and 2018. The first project, a first version of an IoT laboratory, is intended for use by industrial professionals and for academic research and engineering education. The second project, the development of a hardware-in-the-loop (HIL) valve, is intended for use in an electrical engineering course on industrial control systems. Finally, we present a third project on the development of a MIDI sequencer "impinator" (demonstrator), a physical music device intended for recruitment of new students and public display but also for incorporation in student projects.

A. *Internet of Things Laboratory*

In an age of electrification, digitalization, and automation, more and more physical devices, vehicles, home appliances, etc. are becoming interconnected through IoT. Not only does this enable collection and sharing of sensory data that were previously unavailable, it also enables remote and automatic control of such cyber-physical systems. Electrical engineering students, and perhaps automation engineering students in particular, must therefore be trained and obtain hands-on experience with IoT-related challenges and opportunities relevant for the industry. In contrast with standard educational laboratory equipment for students learning about control systems or signal processing, there are not many ready-made IoT solutions for laboratory practice openly available in the market.

At our university, we have a long-standing cooperation with the national maritime industrial cluster, which is strongly represented in our region and has its geographical heart at the Norwegian Maritime Competence Center just across the street of our campus. Addressing both the industrial and educational need for exploring IoT, this project was designed to build up a physical IoT laboratory in close cooperation with some of our partners from the maritime industry. The students involved in this project set up a physical room with common sensors and other devices used on-board ships and offshore installations. In another room on a different floor, equipment was set up for data harvesting, communication, and control. A number of common communication protocols, interfaces, software, and hardware was interconnected and investigated to enable a realistic emulation of maritime cyber-physical systems in action.

The project has focused particularly on the use of MQTT in cloud, fog, and edge computing environments. Message Queuing Telemetry Transport (MQTT) is a publish-subscribe protocol running atop of TCP/IP and dates back to 1999. It was developed by Andy Stanford-Clark of IBM and Arlen Nipper of Cirrus Link. With the recent advances of IoT the popularity of the MQTT protocol has boomed. Since MQTT is based on publish-subscribe functionality and has a small code footprint it is well suited for small embedded devices and costly or narrow bandwidth applications [51]–[53].

This first version of an IoT laboratory will be further developed and utilized both for training and experimentation

of industrial employees as well as integrated in student projects and courses taught at the engineering programs at our university.

Fig. 1 demonstrates development of an example application of light control using a smartphone.



Fig. 1. Development of wireless smartphone light control system.

B. Hardware-in-the-Loop Valve

HIL simulation has been widely used in the industry for many years but perhaps to a lesser degree in engineering education. Ordinary physical equipment for student laboratory projects is limited to the properties and characteristics of the particular hardware being used. This can to some degree be compensated for by investing in several different kinds of equipment, which both occupies physical laboratory space and is costly, or by means of simulators. However, a drawback of using simulation is that students are not faced with the physical hardware, systems and signals may be idealized and unrealistic, and students do not get the practical experience they need. HIL simulators, on the other hand, combine the best of both worlds by offering a physical interface and realistic operation of hardware whilst enabling customization and an “unlimited” range of test cases through software simulation. In addition, using HIL simulators remove the risk of injuries and safety requirements (e.g., completing a safety course before operation) sometimes associated with real equipment.

In this project, students built a HIL simulator of a classical on/off valve with position feedback. The HIL valve can be

connected to an external device for communication and control through a standard industrial interface. This enables students to interact with the HIL valve (e.g., using a microcontroller or a PLC for opening or closing a valve or receiving sensory data or fault messages) as if a real valve was connected. A number of standard industrial valves can be parameterized and simulated in the HIL valve simulator, incorporating realistic physical signal responses in control procedures, testing and verification, and common operational failures. A prototype of the HIL valve simulator with support for both 5V and 24V logic levels was tested, and after minor adjustments 6 identical units were produced. These units have already been adopted in laboratory exercises in a course on industrial control systems.

Fig. 2 demonstrates development the HIL valve. We present



Fig. 2. Development phase (top) and final HIL valve unit (bottom).

more details about our work on the HIL valve in a separate paper submitted to this conference [reference to be included].

C. MIDI Sequencer Imponator

An imponator, or demonstrator, is a physical device designed to impress bystanders and is commonly used on stands for attracting attention. At our university, we regularly host “open days” where the industry, authorities, schools, and the general public are invited. On these occasions, there is a huge need for imponators that attract attention and demonstrate our ongoing educational and research activities. To this end, a student built a MIDI sequencer imponator (MSI), which is an interactive music instrument where “beats” generated from 8 different instruments are multiplexed (mixed) into one looping soundtrack. The beats are configured by physically placing smooth spheres of steel (large ball-bearing balls) in an array, where the rows determine which instrument should be used and the columns determine the temporal position of a beat. In addition, a knob provides variable beat tempo. With some added LED lights for effect operating in conjunction with the beats, the MSI is a cheap and easy-to-use device that bystanders are keen to test out themselves and that demonstrates a number of key concepts that our engineering students face during their degrees. Due to its simplicity anyone can operate it, from small kids to elderly people. Hence, the MSI is a great example of how to make advanced equipment simple to use.

The MSI can also be incorporated in laboratory projects where students can build a new one from scratch, modify hardware and software of an existing prototype, or interface it with other equipment, e.g., a robotic manipulator for “playing music” by moving the balls around.

Fig. 3 demonstrates development of the MSI.

IV. DISCUSSION

Through supervised student labor, the projects presented above were all successfully completed during the two-month summer breaks of 2017 and 2018 and ready for adoption in classes the following semesters. All projects used low-cost commercial off-the-shelf (COTS) hardware and interfaces as well as standard software and protocols.

We discuss some advantages and challenges with our approach below.

A. Advantages

1) *Low Cost:* Pre-made commercial educational laboratory equipment is typically an order of magnitude (tenfold or twentyfold, say) more expensive than low-cost COTS hardware for self-assembly. Adding in the development cost of design and labor reduces this difference but we still believe there is much to be saved because we employ student labor at a comparatively low rate. Cost could be further reduced if assembly is taking place as part laboratory projects or assignments in existing courses, in which students work for free.

2) *Attractive Risk-Reward:* There is little downside to our approach. In a worst-case scenario where the project fails, e.g., the end-product does not work as intended, the equipment still has value and can be disassembled and re-used later; the

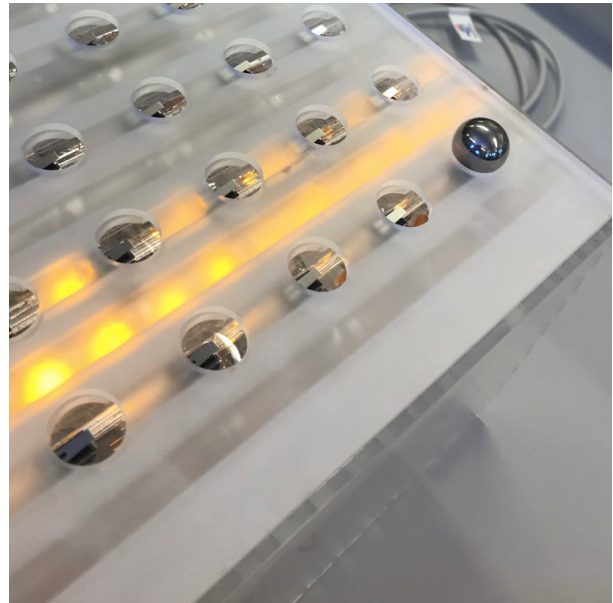


Fig. 3. Development phase (top) and top view (bottom) of MSI unit.

students doing the work will still have learned something from the process; and knowledge and experience from the project can be used by the teacher in future project ideas. If the project succeeds, on the other hand, there is good upside as demonstrated in more detail below.

3) *Rapid Prototyping:* Using student labor in summer breaks means that it is possible to go from a teacher’s project idea late spring to a working prototype or even finalized end-product ready for adoption in classes by the end of summer. In contrast, teachers and lab engineers doing the same work crammed in among other tasks would typically end up spending 1–2 semesters or more on completion. Alternatively, one could pay internal staff for overtime, or hire an external engineer, both of which are expensive solutions.

4) *Customized Pedagogical Design:* Compared with pre-made commercial solutions, the teacher has freedom to customize the laboratory projects in accord with the technological and pedagogical needs of the course in question.

5) *Student Perspective:* Employing students in the development process means that the teacher can gain insight into

the student perspective of challenges and learning outcomes and integrate this insight in further polishing and preparation for class adoption.

6) *Students' Learning Outcome*: Students who undertake the implementation of the laboratory process will learn a lot and gain useful experience, which not only will better qualify them as engineers but also means they can contribute to spawning new and interesting projects or be re-hired as student assistants.

7) *Re-Employment of Students in Class*: The students who were hired during the development phase can be re-employed as laboratory assistants when the laboratory projects get adopted in class. Access to fellow students with first-hand experience and a similar skill-set supplemented by the teacher's deeper academic knowledge can greatly improve students' learning.

8) *Early Adoption of Technology*: Our approach means that we can adopt the very latest of technological advances in educational laboratories. Pre-made commercial solutions will typically lag behind new trends and advancements, or be too costly at an early stage to adopt.

B. Challenges

1) *Variability in Student Competence*: The risk of hired students being unable to finish a project on time or at all increases with lack of competence. We recommend using second-year or final-year students with whom the teacher is familiar with their competence and ability to cooperate (if not working alone). We also recommend running a short interview and carefully explain what is expected from the project before hiring any student. It can also be a good idea to save some funds for follow up work in the autumn semester either by the same student(s) or someone else in case some finalization of the project is needed.

2) *Design and Pre-Planning*: Poor design and pre-planning of the project by the teacher will increase the chance of failure. The teacher must carefully (i) investigate if current laboratory projects in her class must be modernized, and if so, what technology and pedagogical aspects must be included in a new project; and (ii) design a sufficiently detailed and clear project plan and specifications that the students can work independently on over the summer.

3) *Vacation Availability*: Students may need help during the development phase from the teacher but teachers tend to be away from campus 3–4 weeks or more during the summer vacation. In addition to a good project plan as described above, the teacher should be prepared to offer some assistance and supervision despite being off-campus, and/or delegate such as responsibility to a fellow colleague on-campus in this period.

4) *Failure of Equipment*: Equipment might need replacement during the development phase. Emphasis should be on low-cost COTS equipment with short delivery times. It can be a good idea to build more than one prototypes (which may be needed in class anyway), in which case failure of component means that students can continue working on one prototype will waiting for a replacement part.

5) *Final Preparations*: Even when projects finish successfully and on time, unexpected challenges may have arisen during the development phase that need to be addressed before class adoption, e.g., the original design contained flaws or shortcomings. Furthermore, insight from the students doing the work can be used to improve the pedagogical aspect, e.g., what information and resources should students be given in class, what will be typical pitfalls, how much time will be needed for a class laboratory assignment, what needs to be modified to ensure a proper level of difficulty, etc.

C. Future Work

Going forward, we will continue to explore how we best can satisfy the need to adopt new technology in our labs. A suitable platform for disseminating these and similar results to other universities should be found or developed. A standardized way of sharing both reports, building instructions, CAD drawings, software code, etc. would be of great use to universities around the world.

D. Concluding Remarks

In this paper, we have presented an approach for developing laboratory projects in modern engineering education that can overcome the constant challenge of staying relevant and adopting new technology. Students working on the projects have had an economic benefit but more importantly, substantial academic benefits from executing these projects. Future students will benefit from the results in the shape of pedagogically customized and improved laboratory facilities with modern technology. The development costs have been moderate since student salaries are moderate and low-cost COTS equipment has been used in combination with in-house 3D printing and laser cutting.

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