Laboratorios de bajo costo

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1. Introduction

One of the major challenges in engineering education is the development of academic laboratory facilities that enable students to study and solve challenging real world problems. In electrical engineering, and in particular in the area of control systems theory, engineering students must be able to translate feedback design methods taught in lectures into new unexplored practical settings; laboratory facilities clearly play a major role in how students learn and refine these "hands-on" empirical skills [11, 15]. While laboratory practice has influenced formal engineering education for decades, today's state-of-the-art laboratories are noticeably different from those praised and emulated just a few years ago, partly due to the evolving nature of the theoretical challenges in the control community, along with the ongoing advances in technology which determine the tools we use to conduct research (e.g., increasingly powerful simulation programs, Internet access, etc.) [15]. Not surprisingly, there has been an active commitment to innovation in academic [10, 12, 13, 17, 26, 34], and distance learning laboratories [9, 27, 31, 32]. The overall focus has been on trying to overcome the particular difficulties posed when translating new theories into modern affordable laboratory experiments.

Fortunately, recent technological advancements have resulted in the availability of some relatively low cost software and hardware which can be used to support control systems education. For example, in [14] the authors describe the design of a low cost speed control system, which allows students to implement fundamental theoretical concepts on practical problems. More sophisticated low cost LEGO-based experiments (assembled with LEGO Mindstorms kits) are described in [16, 18]. While the authors of [16] focus their experiments in the field of continuous-time control systems (rather than the classical discrete time approach), the authors of [18] emphasize concepts in signal and embedded processing. Both of these experiments are relatively inexpensive (e.g., the three complete experimental setups in [18] can be purchased for $500-600), and not only suitable for teaching but for research as well. Additional low cost laboratory developments in control systems can be found in [22, 23, 35, 20, 21, 30], demonstrating that there has been an honest effort and clear progress towards developing more affordable laboratory facilities.

In this chapter we propose a project for educating engineers via low cost laboratory development. The goal of this project is twofold. First, we want to conduct a collaborative multi-university program for low cost laboratory development for higher education in control systems engineering. Development projects are conducted primarily at single universities by individuals or groups of undergraduates or graduate students, and shared with all universities. It is hoped that before release, the laboratory projects are tested in an educational setting, and all materials, including detailed schematics, suppliers, costs, operational details, laboratory exercises and procedures, supporting educational materials, etc., be provided by development teams (i.e., all materials that are useful to replicate the proposed low cost experiments). We envision that new laboratories will build on older ones, and will change based on advances in technology. Experiments that can serve both undergraduate and graduate programs are highly desirable. More importantly, a strong emphasis is given to very low cost designs (e.g., less than USD $150 per plant), but ones that do not sacrifice educational goals. To jump-start this initiative, we present in this chapter three low-cost experiments which have been developed at the Department of Electrical and Computer Engineering (ECE) at The Ohio State University (OSU), Columbus, OH. These experiments are used in a course at OSU (ECE758 [4]) to help undergraduate and graduate students understand novel theoretical concepts in distributed control systems which are difficult to illustrate otherwise.

The second goal of the proposed project is to provide a service learning experience to PhD students. Generally, PhD-level educational programs lack encouragement to strengthen broader non-technical educational aspects such as: (i) communication skills, both written and oral, and effective teaching strategies; (ii) learning how to develop classroom-based courses/curricula; (iii) learning how to develop experiments and laboratories to compliment classroom-based treatments of theory; (iv) team work and project management; (v) learning how the university system and sources of recruitment for future graduate students work; and (vi) understanding cross-cultural challenges and world-wide development of higher education in engineering. Here, we show how engagement in low cost laboratory development helps PhD students solidify these valuable attributes.

The remainder of this document proceeds as follows. In Section 2, we describe different low cost experiments that were developed at OSU so students can use them in laboratory courses and to conduct research. Then, in Section 3, we suggest some ideas on how to educate PhD students in academic careers based on the development of low cost laboratories. Finally, we summarize and suggest some extensions and ideas for future projects that seem highly promising.

2. Inexpensive control labs

Over the last two decades, there have been ubiquitous developments in information technology (IT). While industry has been able to exploit these ongoing technological advances, universities have shown a lag in terms of developing curricula that suit them. Today, two research and educational forces trying to close this gap in IT usage are cooperative robotics and wireless sensor networks. The first area seeks to understand how a group of ground, underwater, or flying vehicles are able to coordinate their actions effectively. Many universities have developed courses that fit this line of research (e.g., see [6], [2]), and implemented experimental testbeds where vehicles with onboard microcontrollers and some type of communication network try to accomplish a common global objective, but in a distributed fashion. The latter area has also had much recent advancement, in particular over the last five years. One of the leading academic laboratories in this area is at the Univ. of California Berkeley, where matchbox-sized devices outfitted with wireless radios and sensors (called “motes” [3]) are used to study distributed networked control and estimation problems (e.g., tracking of an evader moving through a field of sensors).

The development of laboratory experiments to study distributed networked control systems re-mains expensive (e.g., the Cricket Developer's kit of motes costs approx. $2000). Here, we present an alternative approach to provide laboratory experience for distributed systems at low cost. Al-though they share some similarities, the problems we describe below are different from those studied in cooperative robotics and wireless sensor networks. In particular, here we focus on open challenges from IT-enabled feedback control such as dynamic resource allocation, feedback scheduling of tasks, decision-making over networks, and nontraditional control objectives [25]. The experiments that we introduce to study these challenges are the following:

1. *Balls-in-Tubes Experiment:* Four balls are levitated to a common maximally elevated position by dynamically allocating air flow to four tubes that hold the balls. In one approach, only one air pulse can be applied at a time and to succeed, the control system "juggles" the balls. The juggling is especially challenging due to significant ball-height sensor noise, air turbulence, ball-to-ball coupling via a common air source, actuator bandwidth limits, and the need for distributed decision making over a network.
2. *Electromechanical Arcade:* Two agents must cooperatively fire laser guns at photocell targets in order to maximize the team's point gain within a finite time period. Feedback scheduling is needed due to the unpredictable appearance and disappearance of targets. Distributed scheduling over a network makes coordination particularly challenging.
3. *Planar Temperature Grid:* The experiment has a regular planar grid of 16 zones, each of which has a temperature sensor, heater, and controller interface. The goal is to allocate a limited amount of available electrical current to the heaters in order to maximally elevate the temperatures of all the zones to a common value. The dynamic allocation is complicated by interzone coupling, ambient temperature influences, and wind currents. Moreover, the presence of the communication network between zones, with possible topological constraints on information flow, necessitates the use of distributed decision making.

The first two of these experiments were originally proposed by the authors as a senior project in the Winter Quarter 2002, and the last one was part of the first author's master thesis. While all these experiments are described in detailed in [29] (where actual photos and experimental results can be found), we will briefly overview their basic construction and contribution to the development of low cost laboratories. Our objective is to highlight how low cost laboratories can still present interesting experimental and research challenges.

2.1 The balls-in-tubes experiment

The balls-in-tubes experiment was designed to be an inexpensive testbed for dynamic resource allocation strategies that must exploit feedback information from the plant in order to succeed. Figure 1 shows a layout of the balls-in-tubes experiment. There are four modules, each of which has a tube that holds a ball inside, a fan at the bottom to lift the ball, and a sensor at the top to sense the ball's height. For each tube, there is a box that the fan pressurizes. We can think of this box as a stiff balloon that is "blown up" by the fan, but which has an outlet hole used to blow air into the tube. The tubes are connected at the fan inlets via an input manifold which has an inlet at the bottom as indicated. There is an output manifold at the top of the tubes with an outlet as shown.

The presence of the manifolds is a key part of the experiment. The manifolds force the sharing of air at the input or restrict air flow at the output; both cause significant coupling between the four tubes. Characteristics of the coupling can be adjusted by, for instance, making both the inlet and outlet have different opening sizes. Alternatively, solid objects can be placed inside the input or output manifolds to obstruct air flow. Air flow characteristics are quite complicated due to air turbulence in the manifolds, pressurized box, and tubes. For a range of input manifold inlet sizes, a fan only succeeds at lifting the ball at the expense of other balls dropping. This feature leads to the need for what is called "resource allocation" [19], where here the resource is the air that elevates the balls. The input manifold implements what is sometimes called a "multivariable saturation constraint." There is, under some conditions, a fixed total amount of air coming from the input manifold that can be allocated, and if significant amounts are allocated to some tubes, the fans for the other tubes experience a limitation in what they can allocate.

Beyond the obvious isolated balancing of a single ball in a tube, there are a number of control objectives and challenges that can be studied for this experiment:

1. Balancing the balls inside the tubes, trying to allocate air flow to keep all the balls at fixed positions or alternatively, at a uniform height but maximally elevated.
2. Balancing and reallocation dynamics in the presence of plant changes due to manifold inlet size changes, or flow obstructions in a manifold.
3. Effects of using distributed networked decision making in the presence of an imperfect com-munication network can be studied.

The total cost of the plant is less than $50 per module for a total of at most $200. If the modules are designed to be easily separated, each could be used at a laboratory station to study the control of ball height in a single tube.

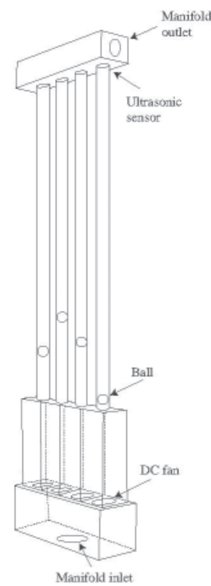

Figure 1: Balls-in-tubes experiment. Each tube has a direct current (DC) fan, a ball, and an ultrasonic sensor. At the bottom, there is an input manifold inlet, and at the top there is an output manifold outlet. These manifolds force the sharing of air at the input, or restrict air flow at the output.

2.2 The electromechanical arcade experiment

The electromechanical arcade experiment was designed to be an inexpensive testbed for distributed networked scheduling strategies where feedback information must be used in order to succeed. This experiment is composed of two main components: guns mounted on the shafts of motors, and targets (see Figure 2). Each gun has a laser and a photodetector. To fire a gun, the gun's laser is turned on by a computer. There are a total of eight targets, which are the boxes arranged in an arc. Each target has a single photodetector and two lasers mounted on top, with a laser pointed at each gun. We represent the appearance and disappearance of targets by whether the target's two lasers are simultaneously on or off. When a target appears, we consider it to have "popped up." When a target pops up, a gun can sense its appearance by detecting the target's laser, but only if the gun is pointed directly at that target by its motor. A gun cannot detect the appearance of more than one target at a time. If a gun fires at a target that is currently popped up, it will get a point for hitting the target, if the gun's laser successfully triggers the photodetector on the target. However, the targets also disappear and if fired upon at that time, the gun gets no points. The appearance frequencies of the eight targets are independent of each other. Target lasers are driven by simple timing circuits that can be adjusted by hand to provide different frequencies.

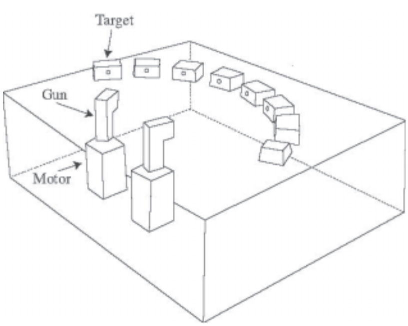

Figure 2: Electromechanical arcade experiment. The experiment has two guns and eight targets. Guns can detect targets by sensing lasers on the targets. Guns get points by firing their lasers at targets when the targets appear. Each gun is mounted on a motor that is under computer control so that the gun can be pointed at different targets.

The two guns are mounted on the shafts of motors that are each driven by an amplifier. Each of these motors has a quadrature encoder that provides the angular position of the motor. We limit the angular velocity of each motor shaft to make the problem more challenging, and make it possible to easily view the firing of guns at targets. We use a PID controller to point each gun to the target that needs to be shot, and these PID control system loops are tuned so that their performance does not impact our scheduling strategies.

The experiment is relatively inexpensive to construct. The greatest expenses are likely to come from the motors and their amplifiers (e.g., one of the motors plus the amplifiers used cost approx. USD$400). However, less expensive motors could be used, since their specifications are not too demanding (high torques are not needed, and relatively low speeds of shaft rotation are desirable so that you can watch the arcade operate). Required gun pointing accuracy is driven by the laser's light dispersal pattern and the size of the photodetector. As long as you keep the targets close to the guns, for typical photodetector sizes highly accurate pointing is not needed. The lasers, photodetectors, and supporting electronics are relatively inexpensive, too (less than USD$250). In fact, the target appearance timing circuits could be eliminated if there are enough digital outputs on your data acquisition board. Computer control of the target appearances would provide a more flexible way to control the pattern of appearances. However, it has a potential disadvantage of not providing for a tangible instructor-induced change to the appearance rates via adjustments to, for instance, potentiometers on the timing circuits during the operation of the experiment. All lasers located at the targets point to a gun photodetector and if one gun is pointing to a target when it appears, this gun can “shoot” at that target, by turning its laser on which triggers the corresponding photodetector of the target. When the photodetector of a target is triggered, the gun considers that specific target to be “hit,” gets a point for hitting the target, and then will pursue another target. The sequence of firings is specified by a real-time scheduling strategy. The analogy with arcade games should be clear.

We assume that the guns do not know any information about the rates of appearance of the targets, but strategies could be invented for estimating appearance sequences. The guns do know a priori the position of all targets, and the guns can communicate about their decisions to process or pursue targets. The challenges for this experiment are as follows:

1. To schedule in real-time a sequence of firings that maximizes the number of points the team of two guns obtains. Since target detection and shooting requires movement of the guns, a good schedule will typically minimize the motion of the guns, and at the same time maximize point gain. Feedback is required to overcome, for instance, uncertainty about when targets appear, or to develop target appearance time estimation strategies. Open-loop precomputed schedules will not be effective if the time allotted to the game is long enough.
2. To cooperatively schedule the shooting of the guns in the presence of an imperfect communi-cation network that allows communication between the two guns. While the network could be the internet and a computer could be dedicated to each gun, networked schedulers

can also be simulated within one computer. Communication imperfections such as random but bounded delays, bandwidth constraints, or message misordering could be considered.

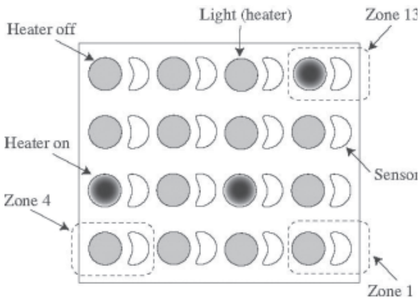

Figure 3: Multizone temperature control experiment. The experiment has 16 individually controlled zones, each with a light for a heater and an analog temperature sensor.

Finally, note that this distributed feedback scheduling problem can be thought of as a type of resource allocation strategy, analogous to how we thought of the juggler, but clearly the dynamics, uncertainty sources, and performance objectives are quite different. Moreover, the resource here is the time dedicated to a target so that allocation is temporal rather than spatial.

2.3 The multizone temperature control experiment

Temperature control experiments are the least expensive experiments we can build that still possess interesting distributed networked control problems. Here, we briefly describe a two-dimensional planar grid of sensors and heaters. This experiment presents both traditional multivariable tracking objectives, and objectives found in dynamic resource allocation problems. The multizone temper-ature control experiment has 16 individually controlled zones arranged in a regular planar grid as shown in Figure 3. Each of the zones has a light for a heater and an analog temperature sensor. Am-bient temperature variations and wind currents have a significant impact. Since the physical layout of the experiment has the lamp in one zone very close to other zone's sensors, there is also significant inter-zone temperature coupling, which manifests itself in self-induced wind currents generated by heater-induced spatial temperature gradients.

The simplicity and low cost make it possible to require the students to construct the experiment themselves. Clearly, such an inexpensive plant could be used in a prerequisite undergraduate course.

The main challenges this experiment presents are:

1. Try to regulate temperature to be uniform across the grid, but with some fixed maximally elevated value. Alternatively, we could seek some fixed or dynamic two-dimensional pattern of temperature values.
2. Try to make one set of zones track the average temperature in another zone, or try to track a reference temperature value.
3. Distributed control with different controllers for each zone and a communication network with random but bounded delays for neighbor-zone sensed information, and delayed control inputs.

These challenges are difficult to meet due to many kinds of disturbances such as ambient temperature, wind currents, and inter-zone effects. Moreover, communication network imperfections present challenges in developing distributed controllers. The cost of this experiment is less than $15 per zone. Supporting electronics include drivers for the lamps that are relatively inexpensive.

Next, we describe how these experiments were introduced in a course called Control Systems Implementation Laboratory (ECE758) at OSU. ECE758 is a 10-week elective course that provides undergraduate and graduate students with laboratory experience in linear, nonlinear, robust, and distributed control systems [4].

2.4 Embedding low cost experiments into academic curricula

After ECE758 students design and analyze the experiment model (pre-labs are handed-in at the beginning of each lab session), they implement different feedback control techniques and develop appropriate real-time algorithms. During the first five weeks of the course, students initially learn how to properly use the data acquisition software (e.g., dSPACE and LabVIEW), and become familiar with introductory topics in control theory; in particular applying system identification, PID, and linear control schemes. They then move on and implement more advanced control techniques like LQR, observers, and nonlinear control schemes. In week 6, the students implement a smaller version of a multizone temperature controller in order to gain insight into the challenges highlighted above. During these six weeks of the course, the students work in small groups with members rotating on a weekly basis in order to promote teamwork and a dynamic interaction within the class.

The final four weeks of the course are intended for students to study a particular topic of interest in more depth. Over the last six years, several students have chosen to work on the low cost ex-periments presented in the previous sections, and implemented various advanced control techniques. For instance, a fuzzy controller was implemented for the balls-in-tubes experiment, followed by a cooperative controller which synchronized the oscillation of the balls in two tubes. Moreover, students implemented a bio-inspired control scheme (based on the prey model, a classical model from behavioral ecology [33]), using a smaller version of the multizone temperature control experiment (see [28] for details). Low cost experiments have not only been demonstrated to be well suited to illustrate fundamental control concepts (in our case, in distributed network feedback systems), they were surprisingly favored over traditional educational experiments (e.g., the inverted pendulum, the 2 DOF helicopter, the cube, and the coupled tanks [8]; hardly any experiments for distributed control are developed by Quanser, Feedback Instruments Limited or PendCon to date).

In summary, ECE758 students are able to design and implement a variety of control schemes, run experiments, and interpret experimental data, which together strengthens the student's ability to identify, formulate, and solve real world engineering problems. They are expected to provide a written report for all the experiments they complete, and give an oral presentation overviewing the results of their final projects. Combining these procedures with the teamwork experience they gain, ECE758 clearly embraces the academic program outcomes a) through g) and k) aspired by ABET [1]. Our own experience suggests that engineers can be educated via low cost experiments and without sacrificing educational goals. In addition, we describe next how the development of low cost laboratories itself helps graduate student develop attributes which enhance their opportunities in future careers.

3. Service learning project

As one might expect, PhD-level engineering graduates often seek employment in academics as faculty members, or in research groups in industry and government laboratories. Their technical expertise and know-how make a perfect match with the demands of such researchoriented institutions. How-ever, national-level studies have identified the need to educate these PhD students on broader, non-technical aspects, in particular to understand the value of good communication skills, team work, project management, economic and globalization issues, and cultural diversity. For instance, when PhD graduates pursue academic careers, they must show good communication skills that allow them to clearly express their ideas in order to develop effective teaching and research strategies. They must also know how to work with groups of students, develop syllabi, and academic laborato-ries. Needless to say, PhD students should start acquiring some of these skills as soon as they start their PhD program, but more often than not they are postponed for when graduates become faculty members (in part due to the tremendous pressure they face to master the technical content of their programs in the first place).

Here, we envision developing low cost laboratories as an opportunity for PhD students to enhance such non-technical attributes which are needed to pursue a successful academic career. It is with this in mind that OSU, with the support of a student organization called Engineers for Community Services (ECOS) [5], has developed a service learning program to help aspiring faculty members achieve their goals. The essential idea of the project is to have a professor lead a group of students to develop short courses with low cost laboratories for international institutions of higher education. Student tasks include development of the content of a course along with its laboratory experiments (e.g., pre-labs, lab manual, etc), and delivery of the experimental settings. Participating students are responsible for preparing their set of lectures notes and exercises and benefit from the experience by:

- Learning how to design a short course.
- Developing and implementing appropriate teaching strategies.
- Gaining experience in developing course material.
- Practicing how to lecture.
- Developing other valuable non-technical skills (e.g., enhancing their communication skills by interacting with people from different cultures).

Low cost laboratory development complements the associated lecture courses and furthermore ben-efits the target institutions by:

- Allowing local students to test fundamental theoretical concepts.
- Setting up local experiments at low cost.
- Proving experimental settings which are robust, easy to maintain and extend, so additional research can be conducted locally.
- Providing a guide of laboratory procedures (possibly field experiments) and related exercises.
- Motivating students to pursue graduate studies and life abroad.

The first two authors of this chapter were fortunate to have participated in the project as OSU graduate students first hand. The third author was the one who created the program and led the experience. In the summer of 2004, the three of us went to Colombia to give a couple of short courses in Cali, Medellin, and Bogotá. The courses taught were divided into two parts: (i) a lecture on biostrategies for optimization, control, and navigation (with examples illustrating distributed control schemes and stability concepts in multi-agent systems), and (ii) a cooperation effort to develop international educational laboratories in feedback control engineering. Our efforts triggered research developments by some of the attendees (e.g., Universidad del Valle, Cali, developed a testbed for multizone temperature control based on the one presented here, and is using it for their current research [24]). Moreover, one of the attendees became a master's student under the supervision of the first author, and another one went to Germany to pursue his PhD studies there, suggest the strong impact that service learning programs can have on the development of the people in target countries.

The service learning program is intended to grow so that graduate students can choose a tar-get country according to their interests and learn about its history, culture, and current state of development in higher education. For instance, in 2005 the second author gave a short course on cooperative control, and an overview of the laboratory development program at Universidad Na-cional Autónoma de Honduras (UNAH) in Tegucigalpa. He studied some of the cultural issues in Honduras, which helped broaden his view of higher education outside the United States. The main idea being that the broader perspective that can be gained in this program helps future faculty members to understand potential advisees from all over the world. We hope that PhD students that participate in this program will help undergraduate students at targeted institutions get admitted and succeed at top research institutions.

Ultimately, the goal of the service learning program is to establish long-term research collabora-tions of world-class researchers in developed countries with the best counterparts in less developed parts of the world. The benefits of such collaborations are mutual. Developed countries benefit from working with leading scientists from other countries in related problems and potentially reducing the costs of certain research projects. Less developed countries benefit from the service learning program because it enriches their local research opportunities and strengthens local institutions with up to date scientific knowledge and cutting edge research.

4. Conclusions

The purpose of low cost laboratory development is two fold: (i) to develop experiments which are inexpensive to construct, well suited to illustrate theoretical concepts, and interesting enough to conduct research; and (ii) to start a service learning program where PhD students are able to develop valuable non-technical skills necessary to pursue a successful academic career. In this chapter, we introduced three low-cost experiments which have been extensively used in education [4], as well as in research [29]. From an educational point of view, it is clear that universities in both developed and developing countries can benefit from low cost experimental settings. In the case of the Department of Electrical and Computer Engineering at The Ohio State University, the low cost experiments have helped students who want to study dynamic resource allocation, feedback scheduling of tasks, decision-making over networks, and nontraditional control objectives in control systems theory start their research. From a research point of view, low cost experiments have helped students in developing countries (e.g., Colombia and Honduras) to enrich their research by illustrating the challenges of cutting edge research.

Every time a novel experiment is developed, we envision that all pertinent information to be made accessible to the widest possible audience, i.e., via a wiki-site where all interested parties is able to upload their contributions [7]. As a result, experiment schematics, suppliers, costs, operational details, laboratory exercises and procedures, and supporting educational materials are available to anyone around the world. We view the proposed project to be a shared effort to spread knowledge, especially to those universities which do not have enough resources to afford a costly laboratory setting for control systems. In our experience, we captured the student's interest in low cost experiments through the senior projects which are generally required to get the B.S. in engineering at an ABET accredited institution. In particular, two of the three low cost experiments proposed here were originally developed in a senior project class (ECE682), and later extended by students who wanted to get more insight into non-conventional control techniques. The efforts of the students to design and implement low cost experiments resonate with the program outcomes of the ABET criteria (i.e., criterion 3, outcomes a) through g) and k)), enriching the educational experience of undergraduate and graduate students.

There are still challenges in developing low cost laboratories (e.g., a cheaper version of data acquisition cards and software packages are needed). Other classes of experiments in control systems (e.g., servomotors, coupled tanks, mobile robots) and experiments for other academic disciplines must be developed. Hopefully, if leading universities across the globe are willing to contribute to the effort of developing low cost experiments, common experimental platforms will encourage international research collaborations and promote educational exchange programs.

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