Smart Objects for Engineering Labs:
Boosting Exploratory Learning in Higher Education

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Abstract—Smart Objects, the constituent elements of the Internet of Things, are computationally enhanced everyday objects such as shoes, fridges, tools, and more. In education, they have the potential to boost exploratory learning of engineering concepts by providing real-time information to students during their learning activities. With this goal in mind, we developed the Smart Cube: a Smart Object for physics courses. This device – by means of an embedded acceleration sensor, a WiFi radio, and a microprocessor – provides real-time acceleration measurements and when combined with an Augmented Reality interface allows students to explore concepts such as normal force and friction. This article presents the design of our first prototype and reports our first experiments on the use of the Smart Cube in an undergraduate physics laboratory course. Preliminary results show a good acceptance and user experience by the students and point towards possible benefits in deeper understanding of engineering concepts.

I. INTRODUCTION

Smart Objects are computationally enhanced versions of everyday items such as tools, clothes, household appliances, jewelry, materials, and more. Using embedded sensors and miniature computers, they are capable of processing information about its use and surrounding environment and relaying it to the Internet. Smart Objects are the constituent elements of the Internet of Things (IoT) and are currently being used in a plethora of application domains such as industrial manufacturing, home automation, health-care, and education [1]–[3].

In Education, Smart Objects have the potential to foster exploratory learning by providing real-time information to students during learning activities [3]. Exploratory learning improves the quality and depth of education by letting the student experience, explore, reflect, and test the concepts presented on a learning environment [4]. With this goal in mind, we developed a Smart Object prototype: the Smart Cube. This device, by means of an embedded acceleration sensor and a WiFi radio, calculates and transmits its acceleration data to a nearby mobile device. The mobile device processes the acceleration data and superimposes relevant information (e.g. force vectors acting on the object) over the Smart Object using the Vuforia Augmented Reality (AR) framework (Fig. 1). A student will then use the information presented by the mobile
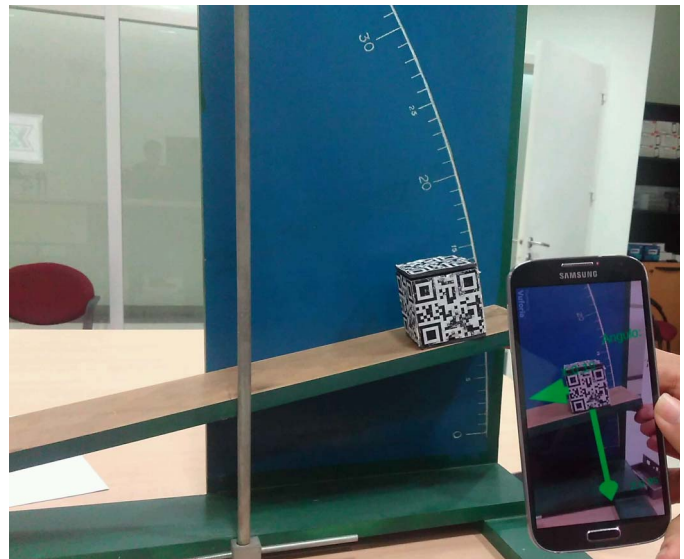

Fig. 1. The Smart Cube transmits acceleration data to a mobile device, which is then translated into superimposed force vectors using Augmented Reality.

device and the Smart Cube to interactively explore and learn a specific concept (e.g. weight, friction, and normal force).

We tested the Smart Cube in an entry-level undergraduate physics course at our institution by including it in static/kinetic friction laboratory exercises and measured the student's learning and user experience. This article presents this work and is structured as follows: section II discusses previous and related work, section III describes in detail the design of our prototype, sections IV and V describe the experimental methodology and the corresponding results and a brief discussion and conclusion is presented in sections VI and VII.

II. RELATED WORK

Usage of Smart Objects in education, while sparse, goes back to the early 2000s [3]. In this section however, we will focus only on previous work that uses AR to interact with Smart/Dumb Objects with a potential or explicit application in an educational domain.

The most salient and relevant example of Smart Objects and AR is the Open Hybrid project at the Media Laboratory in MIT [5]. In this project, Victor Heun et al. created a system that allows users to control and provision Smart Objects using a rich AR interface. Open Hybrid uses the Vuforia AR framework to render the AR interface together with three.js. There are no educational applications of Open Hybrid yet but the authors mention education as a possible future scenario [6].

Equipcodes, a company based in the United States, uses AR to overlay instructions and information over machinery and tools [7]. Their application domain is professional training for technicians and customers of industrial equipment manufacturers. Their technology is proprietary and there are no known implementations yet using Smart Objects.

The authors in [8] used Google Glass to let high school students explore in real-time the results of acoustic resonance experiments. Using a mobile App installed on the Google Glass device, the students where able to explore how the acoustic resonance of the glass changed as it was filled with water. The authors demonstrated that the students were motivated and reached their learning goals.

In [9] the authors created a proof-of-concept system that uses AR to augment the information presented in a physical object (e.g. a map) or information presented in a multimedia physical object (e.g. a TV set). They used OpenGL ES to render the AR layer on a mobile device and RFID tags instead of image tracking to detect and locate objects of interest.

While there are systems that fully combine the use of AR and Smart Objects [6], [10], to the best of our knowledge there are no known applications yet that fully exploit the integration of these two technologies in the educational domain.

III. DESIGN

Laboratory activities are the traditional form of exposing students to hands-on and active learning of engineering concepts. During these activities, students are normally supervised by a teaching assistant who briefly explains the session's learning objectives and the usage of the laboratory equipment. To be effective, the laboratory session must achieve, among several others, the following goals [11]:

- develop intuition and deepen understanding of concepts,
- develop critical, quantitative thinking,
- and test important laws and rules.

The design objective of a Smart Object in a laboratory should be then to boost these three goals through the use of IoT technology.

We used the laboratory sessions of entry-level physics courses at our university as our test learning environment. In particular, we saw an opportunity in inclined plane experiments where concepts such as friction and force components are explored. Therefore, we designed the Smart Cube, a Smart Object that allows students to explore the physical phenomena behind these concepts.

According to Felder and Brent, the use of simulations and virtual laboratories in learning environments have the poten-
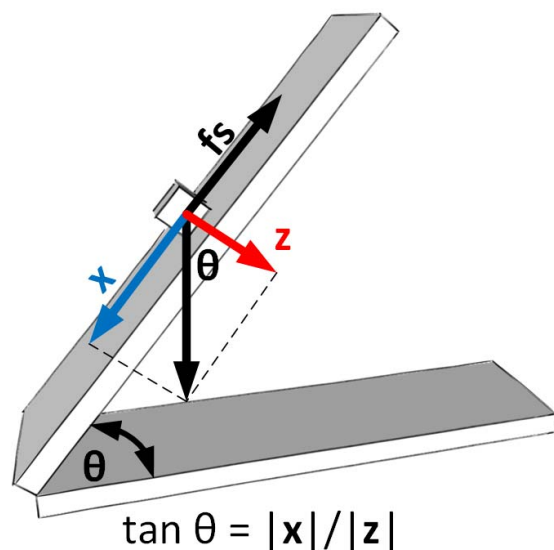

Fig. 2. In an inclined plane, the force of gravity can be resolved into two components: **x** and **z**. The ratio between their magnitudes is equal to the tangent of the inclination angle.

tial to "enable further exploration of hands-on experiments" [12]. Smart Objects can combine the flexibility of a digital simulation without surrendering the hands-on experience, thus boosting the benefits of exploratory learning. Consequently, the design of our Smart Object is guided by the following principles:

1) Provide real-time measurements of the observed physical phenomena to the learner.
2) Be responsive to the physical manipulations of the learner.
3) Be unobtrusive to the learning process.
4) Be a metaphor or replacement of objects used in previous versions of the laboratory exercise.

A. Smart Cube

The Smart Cube was designed to highlight the components of the force of gravity in inclined plane laboratory exercises. In such exercises, an object is placed over a tilted surface while a student slowly increases the inclination angle of the surface. At small inclination angles the object remains at rest due to the balance between the force of static friction f_s and the vector component **x** (see Fig. 2). At some specific angle, **x** overcomes the static friction force and the object starts sliding down the surface. The student records this angle and uses it to calculate the static friction coefficient between the object and the surface. The reverse procedure: start with a high angle and a moving object, decrease the inclination angle, and record the angle when the object stops, is used by the student to calculate the kinetic friction coefficient. In both cases, the friction coefficient is equal to $\tan \theta$ or the rate between the magnitudes of vectors **x** and **z** (Fig. 2).

The Smart Cube uses the Particle Photon, an IoT hardware development platform, to process and transmit data via WiFi.
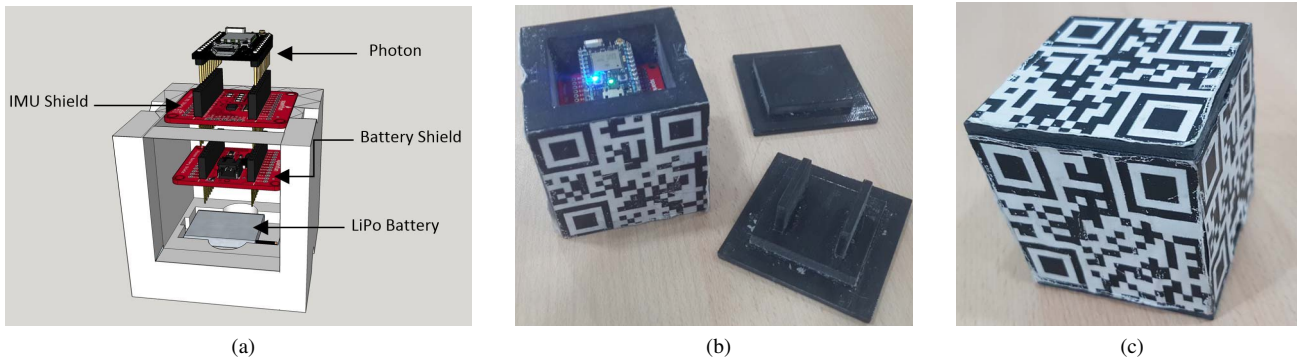
Fig. 3. The Smart Cube uses a Particle Photon device for data processing and transmission via WiFi, an Inertial Measurement Unit (IMU) shield for data capturing, and a battery shield with a 400 mAh LiPo battery for power (a). The casing is 3D printed and consists of an interchangeable bottom cover to test different surfaces and a top lid designed to fasten the internal components (b). Five sides of the Smart Cube are covered with fiduciary marks to aid visual recognition (c).
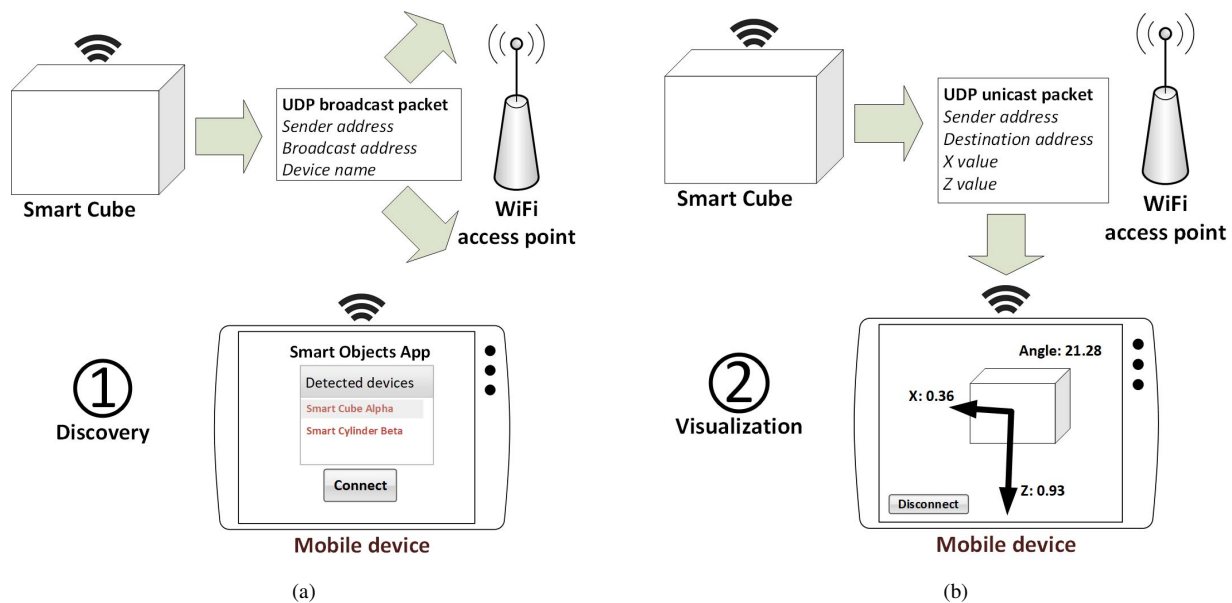

Fig. 4. The Smart Cube uses WiFi for wireless communication with our Android App. This communication process has two stages: discovery and visualization. During discovery, the Smart Cube transmits a UDP broadcast with a unique device name identifier. The Android App receives this broadcast and presents the user with a list of discovered Smart Objects (a). After the user has selected the desired Smart Object, the system enters the visualization stage where the device sends unicast UDP packets to the Android App with the sampled acceleration information (b).

This platform supports hardware add-ons, known as shields, to add extra functionality. Our device employs two shields: a battery shield connected with a 400 mAh LiPo battery and an Inertial Measurement Unit (IMU) shield to sample acceleration (Fig. 3a).

The casing of the Smart Cube was 3D printed using resin with sides of 60 mm. It consists of three parts: the main housing, a top lid to access and fasten the electronic devices, and a set of interchangeable bottom covers with different surfaces (Fig. 3b). The bottom covers are used to experiment with the friction coefficient of different materials. Our first prototype has three bottom covers with the following materials: resin, metal, and cloth (Fig. 6).

We used the Vuforia SDK to generate an AR client App for Android mobile devices. The App communicates directly with our Smart Objects using UDP broadcast and unicast for faster communication. When the Smart Object is turned on, it sends UDP broadcasts containing a unique identification tag and its IP address. Our App uses this broadcast to present to the user all detected Smart Objects. If a Smart Cube is selected, it will stop the broadcast and start sending uincast UDP packets with acceleration measurements every 10 ms (Fig. 4). The App will then use this data to estimate the force vectors acting on the object and the fiduciary marks on the Smart Cube (Fig. 3c) to estimate its position and overlay the vectors accordingly on the AR plane (Fig. 5). Additionally, the App uses a moving average recursive filter to eliminate noise from the data.

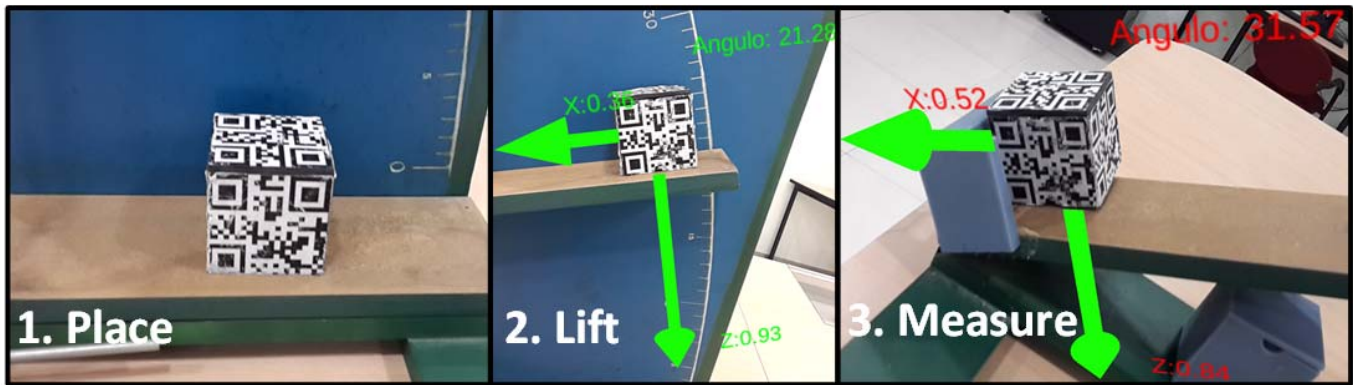The Smart Cube is capable of detecting the stopping shock

Fig. 5. The procedure to measure static friction during a laboratory session is to first 1) place the Smart Cube on a ramp, 2) lift the ramp to increase its steepness while observing the evolution of the vector forces on the cube, and 3) measure the steepness angle after the device slides and hits the stop barrier.

Fig. 6. The Smart Cube has a detachable bottom cover that acts as the contact surface while sliding. During laboratory activities, students measured the friction coefficient of three different contact surfaces : metal, cloth, and resin.

caused when hitting a barrier at the bottom of the inclined plane. This event will cause the Smart Cube to send a stopping message to the client App. The App will in turn stop presenting real-time measurements and display, in red, the last measurement before the collision (Fig. 5). The student will then be able to manually record the magnitude of the forces, and the inclination angle, measured during sliding.

IV. MATERIALS AND METHODS

With the aim of validating our Smart Objects in a real learning environment, we designed an Introductory Physics laboratory session that uses the Smart Cube as a tool to observe and measure the effects of friction between two surfaces. The designed laboratory session had two learning objectives:

- Explain the practical nature of the two types of frictional forces: kinetic and static,
- Measure the kinetic and static friction coefficients between several surfaces in a controlled laboratory setting.

We built two prototypes of the Smart Cube and scheduled our laboratory session in the introductory physics course for all engineering students at ESPOL University (a.k.a Physics I) during one semester.

To reach the laboratory session learning objectives, a student has six tasks: measure static and kinetic friction for three different surfaces using the Smart Cube. The procedure to measure static friction with the Smart Cube is as follows (Fig. 5):

1) Place the Smart Cube on a ramp that is laying flat over the table.
2) Open the Smart Cube App on the mobile device and connect to the Smart Cube on the ramp (each Smart Cube has a unique name that appears on a menu on the App).
3) Slowly increase the steepness of the ramp and observe the evolution of the vector forces on the Smart Cube.
4) When the Smart Cube starts sliding, hold fast the ramp and freeze its inclination.
5) When the Smart Cube hits the barrier at the bottom of the ramp, record the reported inclination angle and vector forces on the App.
6) Use the information on the previous step to calculate the static friction coefficient.
7) Change the contact surface of the Smart Cube and repeat the experiment.

For kinetic friction, the procedure starts with the ramp at a steep angle and the Smart Cube sliding. The student decreases the steepness until friction stops the device, the inclination angle is recorded and used to calculate the kinetic friction. As with static friction, these steps are repeated for each interchangeable contact surface on the Smart Cube: metal, cloth, and resin (Fig. 6).

We also designed a control laboratory session where the Smart Cube is replaced with several dumb objects representing different surfaces (wood, metal, etc.) and no mobile devices are used. The procedure to measure static and kinetic friction is the same except that the inclination angle is measured manually using markings on the ramp.

In total we evaluated the Smart Cube with 24 students of the Physics I course (Fig. 7), 16 students did the control laboratory session. After the session, all 40 students took a quiz that measures the session's learning objectives and the 24 students that used the Smart Cube answered a survey to measure their user experience. The results are presented in the next section.

V. RESULTS

We used two items to measure the effectiveness of the Smart Cube as a learning tool in the Physics I course: a survey

Fig. 7. In total, 24 students used the Smart Cube in laboratory sessions of the Physics I course at ESPOL University.

Fig. 8. All five dimensions of the measured user experience were rated as excellent by the majority of students (75% or more).

Group	#students	Min.	Max.	Avg.	Std.
Experimental	24	50	100	72	13.4
Control	16	50	75	66	12.5

to measure user experience and a quiz to measure learning objectives. The 24 students that used the Smart Cube are referred here as the experimental group and the remaining 16 students are referred as the control group.

A. Survey

We asked the students in the experimental group to fill out a user experience questionnaire after the laboratory session. The students were asked to rate from 1 to 10 the following dimensions of user experience:

1) Interaction with the Smart Object
2) Motivation to use the Smart Object
3) Learning of physics during session
4) Learning of physics thanks to the Smart Object
5) Comparison of the session with traditional sessions

To encourage the students to read the questionnaire and reflect on their responses, we switched the order of the scale in some of the questions and warned them accordingly. Therefore, questionnaires where all answers were marked as 10 were not considered valid. We obtained 23 valid questionnaires out of 24 surveyed students. Fig. 8 shows the results divided for all five dimensions split in three ranges: excellent (10-9), acceptable (8-6), and bad (5-1). Overall, all five dimensions were rated as excellent by 75% of students or more.

B. Quiz

After the laboratory sessions, all students in the experimental group and in the control group took a quiz that measures the two learning objectives defined for the laboratory session. The quiz was graded and counted as extra points towards the final grade of the course.

In summary, the quiz asked the following questions in true/false or multiple choice format:

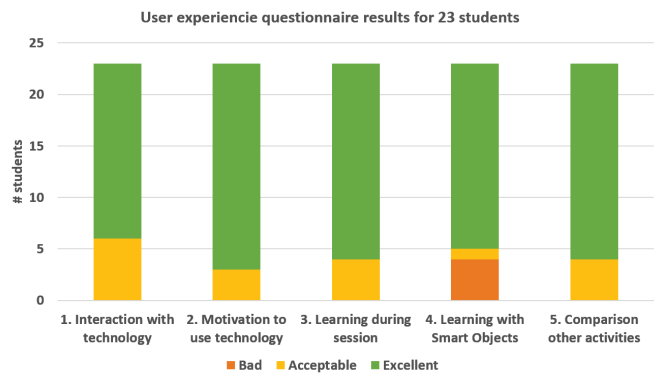1) Being everything else equal, are friction coefficients proportional to the inclination angle?

2) What experimental parameter can you use to estimate the friction coefficient?
3) What are the factors that determine the friction coefficient?
4) Is the kinetic friction coefficient always lower than the static?
5) Does the kinetic friction coefficient change over time?

The results of the quiz, with scores scaled from 0 to 100, are presented in Table I. The average score of the experimental group is 72 with a standard deviation of 13.4 while the control group averages 66 with a standard deviation of 12.5.

The quiz score data failed a normality test (we used a Q-Q plot analysis), therefore we performed a Kruskal-Wallis rank sum test on it. Kruskal-Wallis is a non-parametric method that does not assume normality and tests whether samples originate from the same distribution. Kruskal-Wallis assumes the same variance for both groups; we performed a Levene's test to validate this assumption.

The Kruskal-Wallis test produced a p-value of 0.1572 which is too large to reject the null hypothesis: both groups, experimental and control, come from the same distribution. Therefore, we can't affirm that the difference between averages is statistically significant and, consequently, that the experimental group performed better than the control group in the quiz.

VI. CONCLUSION

The Smart Cube is our first prototype of a Smart Object for a learning environment in engineering courses. It allows students to visualize, using AR, how the component forces of gravity act upon an object while in an inclined plane. Additionally, the Smart Cube is designed to facilitate the measurement of friction coefficients between different types of surfaces.

(a)	(b)

Fig. 9. Our next Smart Object prototype, the Smart Cylinder, allows students to explore the concepts of angular momentum and acceleration in a rotating body.

The feedback from students that used the Smart Cube during laboratory activities was overall positive and points to a beneficial effect of IoT technology in learning environments. However, while the average quiz results of the experimental group was higher than the control group, it is still too early to affirm that the Smart Cube assisted students to reach their learning goals. Several other contributing factors such as the novelty effect of new technologies [13] and pushback from educators and students to new methodologies and technologies [12], [14] can only be taken into account with tests over a longer span of time.

VII. FUTURE WORK

The positive user experience results and attitudes of students have encouraged us to include Smart Objects in future laboratory activities using a larger number of students and a more comprehensive measurement of learning goals. We are working on a second Smart Object prototype, the Smart Cylinder, that allows students to explore the concepts of angular momentum and acceleration in a rolling body (Fig. 9). This prototype, now in beta stage, is capable of measuring angular velocity and acceleration while rolling down an inclined plane (Fig. 9b) and graphing the results. We are developing new laboratory activities that will include these two prototypes in the Physics I course of ESPOL University. On the long term, we envision to include new prototypes in Chemistry and second year Physics courses using custom-made small form-factor hardware components.

Additionally, we plan to open our designs to the IoT and educational community. We are currently working on allowing our educational Smart Objects to interoperate with other IoT systems via integration with open source frameworks such as Iotivity that adopt the Open Interconnect Consortium (OIC) standards [15]. On the educational side, we plan to publish our hardware designs, source code, and laboratory guides using a Creative Commons license in an Open Educational Resource repository [16], [17].

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