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Smartphones as Smart Tools for Science and Engineering Laboratory: A Review

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Abstract
This article reviews a decade of research in transforming smartphones into smart measurement tools for science and engineering laboratories. High-precision sensors have been effectively utilized with specific mobile applications to measure physical parameters. Linear, rotational, and vibrational motions can be tracked and studied using built-in accelerometers, magnetometers, gyroscopes, proximity sensors, or ambient light sensors, depending on each experiment design. Water and sound waves were respectively captured for analysis by smartphone cameras and microphones. Various optics experiments were successfully demonstrated by replacing traditional lux meters with built-in ambient light sensors. These smartphone-based measurements have increasingly been incorporated into high school and university laboratories. Such modernized science and engineering experimentations also provide a ubiquitous learning environment during the pandemic period.

Keywords: Smartphone sensor; STEM education, distance learning, mechanics, optics

1. Introduction

Smartphones have become indispensable tools for communication, multimedia usage, data collection and personal organization. In addition to rapidly developed dual cameras and microphones, several high-accuracy sensors are included in smartphones for various utilities. It follows that smartphones have been explored as portable measurement tools. Numerous demonstrations of inventive measurements using smartphones as integral parts were reviewed [1]. A lot of publications have been focused on healthcare [2]. Pongnumkul et al. reviewed the measurement systems designed for smart farming [3].

The uses of smartphones in Science, Technology, Engineering, and Mathematics (STEM) education have been investigated. The concept is in line with the microcomputer-based laboratory, but the experimental setup is much more compact without a complicated interface of external sensors. Current smartphones are commonly equipped with ambient light sensors, proximity sensors, gyroscopes, accelerometers, magnetometers, microphones, and cameras [4-5]. The working principle itself can be used for teaching electrical engineering. The example by Countryman deployed accelerometers as a case study for the axis orientation and microelectromechanical system (MEMS) [6]. Errors of smartphone-based measurements can

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be analyzed and demonstrated in the case of accelerometers, magnetometers, and ambient light sensors [9]. Hochberg et al. reported the positive effects on students learning physics using smartphones [7-8]. Mobile iOS and Android applications are increasingly developed for specific measurements and are widely available for download. Furthermore, measurement suites such as ‘Physics Toolbox’ [10], ‘Phyphox’ [11], ‘iMecaProf’ [12], and ‘Sensors Fusion’ [13] incorporate several measurements and process the acquired data. A gamified suite offers an innovative route to learning, as exemplified by ‘Physics Toolbox Play’ [14]. Reflecting the advances in technology, chemistry and biology laboratories have also exploited these hardware and software developments to characterize chemical and biological specimens. It is encouraging that these developments lead to engaging science and engineering lessons in higher education. Several research works have been published in academic journals in the past decade. Articles compiling progress in smartphone-based experimentations are beneficial for both students and lecturers because these best practices could be implemented in modern education. The versatility of smartphones as laboratory instruments in studies of motions, waves, and optics is detailed in this review. In addition, prospects of implementations in distance learning are also discussed.

2. Literature search

Literature on applications of smartphone sensors in the laboratory for science and engineering students was collected by searching the Scopus and Web of Science databases. The searches in both databases cover articles from 2011 to 2021, and keywords are “smartphone sensor” AND “laboratory” OR “physics” OR “engineering”. The returned articles are then selected according to the following 3 criteria: (1) it applies the smartphone sensors for educational purposes; (2) it focuses on using smartphone sensors in the science and engineering laboratory; (3) it includes detailed experiments on mechanics, waves, optics using smartphone sensors. By applying these criteria, 83 articles published from 2011 to 2021 and indexed in Scopus and Web of Science databases are included in this review. The published articles are categorized according to the topical lessons and utilizations.

3. Smartphones in studies of motions

Smartphones can be turned into intelligent measurement tools in mechanics laboratories of high schools as well as physics and engineering students. Different motions ranging from free-falling to gliding on an air track and rolling on an inclined plane could be monitored by smartphone accelerometers. The gravitational acceleration can be deduced to compare the accuracy of each free-fall experiment [15-16]. Oprea & Miron analyzed linear motions using either ‘Smart Measure’ or ‘Accelerometer Monitor’ applications with an accelerometer [17]. The translation motion down an inclined plane was studied, and the coefficient of friction between the surfaces was determined [17-18]. Coban & Erol compared an accelerometer and an angle meter in the experiments between different surfaces [19]. A similar motion on an inclined plane was analyzed using ‘Physphox’ [20]. Traditional experiments on the air track were modified by González et al. to compare a frictionless motion and that with friction [21]. The acceleration due to the elastic collision was measured using ‘Sensor-Mobile’ and ‘Physics Toolbox’ suites on Android smartphones [21]. Interestingly, the experiments can be extended from the classroom to the outside environment. Pendrill proposed demonstrations of motions in an escalator and a roller coaster [22]. Vieyra et al. measured the acceleration of an elevator Using a smartphone accelerometer [10]. Kuhn & Vogt demonstrated the accelerated motion with a vertical drop ride in an amusement park [23]. Martinez & Garaizar developed ‘Serious Physics’ for kinematics studies both inside and outside the classroom [24]. This Android-based mobile application differently utilizes four sensors: accelerometer, gyroscope, magnetometer, and touchscreen. Apart from lessons in the basic mechanics, Countryman suggested that a built-in accelerometer could also be used to introduce the general theory of relativity [6]. According to the principle of equivalence, a smartphone and a user can not distinguish the effect of an accelerated frame from gravity.

In addition to the accelerometer, other smartphone sensors and methods could be implemented in studies of motions. Ayop recorded a video of collision and analyzed the effect of impulse on objects using the ‘Tracker’ software [25]. The motions were successfully analyzed by recording the sound of the impact by smartphones [26-27]. Oprea & Miron demonstrated that the GPS unit with the ‘Android Speedometer’ application could trace the distance and velocity as a function of time in motion [17]. The velocity measurements were also demonstrated by using ambient light sensors in smartphones. The accuracy of such experiments could be confirmed by determining the gravitational acceleration [28]. Kapucu detected the light emitted from a toy car, giving rise to its variation in position with time [29]. The acceleration and velocity of translation motion down an inclined plane could also be analyzed [29-30]. Pierratos & Polatoglou used a smartphone light sensor with the ‘Phyphox’ suite to study kinematics in the combined Atwood machine and Galileo’s inclined plane [31]. Alternatively, Nuryantini et al. employed a magnetometer with the ‘Physics Toolbox’ suite to determine an average velocity of a smartphone-attached object [32]. The velocity was indirectly obtained from a variation in a magnetic field with the distance of the moving smartphone away from the magnet on the track. Based on the dependence of pressure on altitude, the vertical motions of elevators and drones were analyzed by the pressure sensors installed in a smartphone [33].

Studies of the rotational and circular motions also differ in terms of the sensors used. Radial accelerations by the centripetal force were analyzed using smartphone accelerometers [10, 34-36]. Besides, a gyroscope was exploited to study the rotation motion[37-40]. The gyroscope and accelerometer were combined to verify the dependence of Coriolis acceleration on the angular velocity of a rotating track [41]. Aided by ‘Phyphox’, the frequency and acceleration of a turntable were successfully analyzed [42]. Kapucu utilized an ambient light sensor to track the motion of a light-emitting toy train [43], and a proximity sensor to study the circular motions of a propeller [44]. Besides, the sound recording determines the angular velocities of a clock’s second hand and a metronome [45]. Sriyanti et al. determined the moment of inertia of rotating sphere, disk, cone, and cylinder using smartphone magnetometers [46]. Using a magnetometer of a smartphone attached to a hollow cylinder, the rolling motions along an inclined plane [47-49] and a curved track were analyzed [50].
Smartphone-based experiments have successfully been designed to analyze different forms of oscillations. Simple pendulum and spring oscillation were studied using accelerometers [51-53]. Interestingly, Listiaji et al. reported that the measurement precision of spring constant using a smartphone accelerometer was higher than that using a video tracker [54]. Nuryantini et al. reported a positive response from students to the smartphone incorporation in a simple harmonic oscillation (SHM) lesson [55]. The measurement accuracy was confirmed by determining the gravitational acceleration value from the pendulum oscillation [56]. Alternatively, a magnetic pendulum was used in the measurement with a smartphone magnetometer [55]. Pili studied the oscillation of an object attached to the spring [57], and the spring constants were determined from the experiments using either magnetic field sensors or ambient light sensors [58-59]. Similarly, Sans et al. deployed an ambient light sensor of a smartphone attached to a spring to measure the variation in illuminance with its oscillation [60]. Gallitto et al. analyzed errors of such smartphone-based oscillations [61]. A proximity sensor was also proposed to precisely measure the oscillation period of a simple pendulum [62]. Using a smartphone, the oscillation of a physical pendulum was analyzed in the case of

large angles [63], and the moment of inertia of a physical pendulum could also be obtained [64]. A smartphone accelerometer was also used to verify the energy conservation in the pendulum oscillation [65]. Besides, accelerometers could monitor amplitudes and periods of the damped oscillations [66-67] and the coupled oscillations [68]. Kaps et al. used smartphone accelerometers and 'Phyphox' to study the motion of a torsion pendulum [69], and an oscillating cylinder in water [70]. Furthermore, Momox & Ortega De Maio incorporated MatLab into the measurement system [71]. For the outdoor experimentations, an accelerometer and a gyroscope were successfully combined to analyze the movement of a pendulum ride in an amusement park [72].

4. Smartphones in studies of mechanical waves

For sound waves, built-in microphones need tailor-made applications to display acoustic spectra. 'Audacity' is one of the applications available to analyze sound characteristics [73-74]. Lessons in acoustic resonance and beats were successfully arranged based on smartphone measurements [75]. The Doppler effect and measurement of sound velocity were also performed [76]. The sound velocities in different gaseous media can be compared [77]. Furthermore, sound waves in daily life can be quantitatively analyzed by using a smartphone-based system. From sound recordings, several physical quantities could be derived [78]. Florea collected spectra from various sources, and characteristic frequencies of household objects were estimated [79]. From the sound detection by smartphone, Hawley & McClain created the map of sound directivity around the speaker [80]. The smartphone-based lesson on acoustic power measurement for engineering students was also proposed [81].

To study the frequency of water waves, a smartphone was incorporated into a ripple tank, and the wave generation was controlled via the 'Phyphox' suite [82]. An experiment using salt solutions was also performed and compared to the water to study the effect of viscosity. Wave images captured on the smartphone were further analyzed. The smartphone imaging of liquid was also employed to measure surface tension [83]. The surface tension was deduced from the geometry of a liquid droplet hung at the tip of a pipette or a tube.

5. Smartphones in studies of optics

The ambient light sensor in a smartphone can replace a commercial lux meter in a variety of experiments in optics. Some mobile applications, available without charge, give the output in terms of illuminance. The inverse square distance law can be verified by placing a smartphone at varying distances from a light source [84-86]. Efficiencies of incandescent bulbs and halogen lamps as light sources were compared using a smartphone light sensor as a light meter [87]. Beer-Lambert's law was demonstrated by comparing the illuminance transmitted through the media [88-91]. The reduction in illuminance of light passing through water could be calibrated to determine the liquid turbidity [86]. Furthermore, Colt et al. modified an experiment to verify Bouguer-Lambert's Law [89]. Chiang & Cheng demonstrated the measurement of Brewster's angle of glass and acrylic by an ambient light sensor [92].

The nature of optical polarization is demonstrated by measuring the changing light intensity according to Malus' law. Several groups have shown that the data measured using a smartphone gives rise to plots of high accuracy [85, 93-94]. The ratio of illuminance passing the analyzer to that of the incident light is directly proportional to $\cos^2\theta$, where θ is an angle between the polarizer and the analyzer. The light measurement by smartphone sensors is also effective in analyzing interference and diffraction patterns, as demonstrated by Diaz-Melian et al.[85] and Shakur and Binz[95]. Malisorn et al. investigated light scattering by measuring a distribution of light intensity [90].

6. Prospects for distance learning

There is still room for exploiting newly incorporated or underused sensors. The latest smartphones are endowed with more sensors, such as a pedometer enabling users to play somatic games and track their physical activities. The built-in thermometer is extended from monitoring heat generated in the phone to ambient temperature measurement. Moreover, biometric units and near-field communication (NFC) sensors are increasingly incorporated. These upgrades ensure the further progress of smartphones for STEM education. Luchsheva et al. recommended the integration of different sensors, digital filtering, and augmented reality technology [96]. Mobile applications for specific sensors are increasingly available for download and the development by engineering students is encouraged [97]. The combination of hardware and software allows instant measurements. It follows that the smartphone based-laboratory can be carried out anywhere and combined with the online discussion of results as well as other multimedia during the COVID-19 pandemic period [98]. Mobile devices have been widely implemented in outdoor educational settings [99]. They become even more helpful when access to the on-site lecture and laboratory are limited. Tzamali et al. reported that high school students have positive feedback on smartphone-based experiments carried out at home [100]. The best practices assembled in this review can effectively complement the virtual laboratory [101], which improves theoretical understanding but does not provide students with hands-on skills. Unlike many conventional experiments, these smartphone-based lessons do not rely solely on laboratories facilities and therefore support ubiquitous and personal learning environments [102]. Like other online lessons, demonstration and relevant information can be supplied online. Carroll & Lincoln recommended the 'Phyphox' measurement suites because of their numerous features and supporting resources on the internet [103]. Moreover, students can develop research projects and innovations based on these measurements. The challenge beyond the goal of science education is to develop automated systems around smartphones for practical uses because smartphone-based experimentations have already shown the potential for professional and point-of-care applications.

7. Conclusions

In addition to other benefits of using smartphones in classrooms, many research and developments have transformed them into smart measurement tools in science and engineering laboratories. With sensors and mobile applications in a smartphone as an integral part, experiments were assembled into engaging lessons on motions, waves, and optics without increasing high-cost equipment and budget. For motion studies, accelerometers were predominantly used, but various experiments based on magnetometers, gyroscopes, proximity sensors, and ambient light sensors were also demonstrated. Ambient light sensors were vital to experiments in optics, whereas smartphone cameras and microphones could capture mechanical waves for further analysis. These hands-on lessons are viable alternatives to on-site lectures and laboratories during the pandemic period.

Disclosure and conflict of interest

The authors declare that they have no conflicts of interest.

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