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Smart scientific instruments based on smartphones: a brief review

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ABSTRACT

Smartphone has gone beyond a communication hub to be a measurement device itself, thanks to various built-in sensors. This article reviewed achievements in transforming ubiquitous smartphones into cost-effective scientific instruments for educational laboratories, environmental studies, point-of-care diagnostics, home-based health monitoring, and rehabilitation. Magnetic fields were precisely measured by built-in magnetometers, leading to demonstrations for engineering and medical applications. The smartphone-based joint-angle measurement was a viable alternative to traditional goniometers. Characterizations of optical signals captured by cameras led to portable spectrophotometers and colorimeters for both educational and practical uses. Interestingly, smartphones became a platform for high-resolution microscopes and fluorescence microscopes were developed with add-on components. These smart instruments become even more attractive options in the pandemic period with limited facility and laboratory access.

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1. INTRODUCTION

Ubiquitous smartphones are integral parts of communication and internet of things (IoT) systems. Information and measured signals are transmitted, stored, processed, and displayed using smartphones [1], [2]. In addition to being a connection hub, any smartphone can perform measurements using its built-in sensors [3]. The measurements by numerous smartphone sensors were initially implemented in science, technology, engineering, and mathematics (STEM) education. Further developments have invented smartphones as measurement tools for engineering applications [1], [3]–[6]. Also, analytical laboratories have greatly benefitted from the imaging and sensing capability of built-in or add-on smartphones sensors [7], [8]. For example, characterizations based on optical absorption, reflectance, fluorescence, luminescence, and surface plasmon resonance have been demonstrated.

This article reviews the innovation of smartphone-based magnetometers, goniometers, spectrophotometers, colorimeters, and microscopes. Inventions of inclinometers and infrared detectors are also mentioned. These instruments are valuable for both educational and professional uses. The realized potential of smartphones as smart instruments is already vital to intelligent systems in engineering [1], smart farming [9], healthcare [10], and environment monitoring [11].

2. UTILIZATION OF SMARTPHONE SENSORS

Current smartphones are commonly equipped with precision sensors and transducers listed in Table 1 [11], [12]. To use them in measurements and characterizations, different sensors need different mobile applications (apps). With specific apps, ambient light sensors and magnetometers in smartphones can respectively act as conventional lux meters and gauss meters in illuminance and magnetic flux density measurements [13]. Sound detected by built-in microphones can be analyzed or converted into sound level intensity. Images and videos captured by dual cameras can be analyzed. In addition to video analysis, velocity and acceleration in different types of motions can be measured by accelerometers, gyroscopes, magnetometers, ambient light sensors, and global positioning system (GPS) [13]. Measurement suites were also developed, enabling the multiple sensing of physical quantities [14]. Apart from those listed in Table 1, more sensors are incorporated into the latest smartphones, including pedometers, near field communication (NFC) sensors, and biometric units.

Table 1. Working principle and function of sensors and transducers commonly installed in smartphones

Sensor/Transducer	Function	Working Principle
Dual microphone	Enable the calls and activate voice commands	The electromechanical transducers convert sound waves into electrical signals
Dual camera	Capture the images and store them in digital form	The lights reflecting from objects are collected by optical parts and converted to electrical signals by complementary metal-oxide-semiconductor (CMOS) image sensors
Touchscreen sensor	Activate commands on the display menu	Touching skin capacitively changes electrical signals on the screen
Ambient light sensor	Adjust screen brightness, according to the surrounding, for proper visibility and battery use	The electrical current is dependent on the ambient light detected by the sensor
Proximity sensor	Detect nearby objects to switch off the screen when the phone is in a pocket or close to the ear	The infrared detector measures the distance between an object and the phone from the variation in infrared radiation
Accelerometer	Detect the axis-based motion to reorient the screen and evaluate the movement	Instantaneous forces are indirectly measured from the capacitance changes by motion in the X, Y, and Z axes
Gyroscope	Detect the angle-based motion to evaluate the direction	Degrees of changes in the orientation are directly measured
Magnetometer (Digital compass)	Navigate the direction and support a geographical map	The electrical current through an anisotropic magneto resistive (AMR) material is dependent on the magnitude and direction of an external magnetic field
GPS unit	Locate position and provide a geographical map	Receive the location data from satellites
Barometer	Measure the altitude of the location	The air pressure is dependent on the height relative to the sea level

3. REVIEW OF SMARTPHONE-BASED INSTRUMENTS

Successful demonstrations of smartphone-based instruments from the literature are categorized into the following five sub-sections according to types of measurement and characterization. The sensors listed in Table 1 were differently utilized with either iOS or Android app. To ensure the accuracy of measurements, each instrument need a calibration with the standard equipment.

3.1. Smartphone magnetometers

Magnetometers equipped in smartphones have been implemented as an alternative to a Hall probe and a Gaussmeter for measuring magnetic fields in science and engineering applications. Arabasi and Al-Taani [15] demonstrated that the sensitivity of the smartphone magnetometer was sufficient to detect the earth's magnetic field. Oprea and Miron [13] measured magnetic fields from ferromagnetic objects using the Metal detector app and electromagnetically emissive sources using the *EMF* Sensor Free app. Using both iOS and Android smartphones, Arribas *et al.* [16] recorded magnetic fields at increasing distances away from different magnets (x). The reduced magnetic field was directly proportional to x^{-3}. Variations in magnetic fields generated by current-carrying wires and loops were also studied using smartphone magnetometers [13], [17], [18]. To confirm the accuracy of measurements, magnetic fields of Helmholtz coils were measured as a function of the current and position and compared to the calculations [19]. An experiment with a moving Helmholtz coil was also set up [20]. Furthermore, Arribas *et al.* [21] measured the magnetic field in a solenoid core as a part of an indirect measurement of the speed of light. Interestingly, Suksmono *et al.* [22], [23] developed a visual mapping of magnetic fields around ferromagnetic objects. Zhao *et al.* [24] demonstrated the tracking of surgical needles by smartphone magnetometers for future assisting a minimally invasive surgery.

3.2. Smartphone-based inclinometer and goniometers

Angle measurement is fundamental in daily life and provides a foundation for engineering and architectural practices. Smartphones can measure the orientation and displacement because built-in accelerometers, magnetometers, gyroscopes, and cameras detect both linear and angular motions [25]. A measurement of off-axis structural displacements was demonstrated using a smartphone gyroscope [26]. Djebli *et al.* [27] attached a smartphone to a ship as an innovative method of testing the ship's stability.

The range-of-motion (ROM) angle measurement in the musculoskeletal system is vital to examine the joints and assess the treatment. The ROM measurement is also applicable to animal joints, as exemplified in equine rehabilitation [28]. ROM measurements by smartphone goniometers were reported and comprehensively reviewed by Keogh *et al.* [29]. Using various smartphone apps, the versatility is demonstrated by examining several joint angles. The use of gyroscopes has been improved predominantly with ROMS measurements of the neck [30] and wrist [31], [32]. Analyses of hip rotation [33] and back pain [34] were also recently reported.

Although the joint angle measurements are primarily associated with physical therapy and sports, the ROM concerning performing arts has increasingly been studied. For example, Steinberg and co-workers recommended that the dancers maintain their natural flexibility through appropriate joint exercises instead of increasing ROMs [35]. Forczek-Karkosz *et al.* [36] measured and suggested the ROMs of anterior pelvic, hip, and knee for flamenco dancers, and the effects of joint hypermobility on ballet dancers were investigated [37]. The hidden Markov model expressed the angular movements in Likok Pulo, Aceh traditional dance [38]. The smartphone goniometer certainly has the potential to explore ROMs in performing arts.

3.3. Smartphone-based spectrophotometers and infrared detectors

Several low-cost spectrophotometers based on a smartphone camera were proposed for examining atomic spectra in high school and undergraduate laboratories [39], [40]. On the other hand, Hosker [41] constructed a spectrophotometer based on an ambient light sensor. Add-on components could be produced by paper crafting or 3D printers. Woo and Ju [40] reported that the spectrophotometer with 3D printed components had a superior resolution to the paper-crafted spectrophotometer. Bogucki *et al.* [42] also utilized a dual-beam spectrophotometer with 3D printed components to verify the optical absorptions according to Beer-Lambert law, and the colorimetric nitrate assays. Markvart *et al.* [43] developed a high-resolution spectrometer based on a smartphone with a self-calibration feature. Smartphones detect not only visible light but also a part of the infrared spectrum. A unique thermal imaging setup by Kubsch *et al.* [44] revealed infrared radiation from the human body. Infrared scattering from ground beef samples was detected by a smartphone camera and could be related to bacteria contamination in the meat products [45]. Furthermore, the proximity sensor also detects infrared radiation, which can be exploited in innovative measurements. The turbidity meter was developed based on the smartphone measurement of infrared scattering in liquids [46].

3.4. Smartphone-based colorimeters

Various colorimetric apps, including Colorimeter, Catch Color, and Color Detector, are available for measuring colors according to red-green-blue (RGB), CIE L*a*b*, and hue-saturation-lightness (HSV) color spaces. This color quantitation by smartphone opens opportunities for several chemical analyses [47]. Color changes in solutions, assays, and pH strips were determined based on the difference in color parameters [48]. Using smartphone colorimetry, the glucose was evaluated based on the CIE L*a*b* color space [49]. In contrast, the magnetic solid-phase extraction of water-soluble dyes was carried out in both RGB and HSV spaces [50]. The bleaching reaction of food dye was successfully analyzed [51]. It was demonstrated that chromium in water correlated to light absorption [52], and the chlorine content could also be measured [53]. Mercury [54] and ammonia [55] were successfully detected using smartphone-based colorimeters. Furthermore, Solmaz *et al.* [56] improved the test strip analysis of peroxide content by integrating machine learning classifiers into smartphone colorimetry.

Smartphone colorimetry has been implemented as a potential alternative to the traditional Munsell soil color chart [57], [58]. Soil color measurements indirectly give rise to iron and organic matter contents [59], [60]. Stiglitz *et al.* [61] showed the combination of smartphone colorimetry and GPS unit to correlate the soil characteristics with the location. In archaeology, a smartphone was used to classify ancient potteries according to their colors from different clay sources [62]. Mulcare and Coward [63] demonstrated the matching of skin color by smartphone for maxillofacial prosthesis. Hong and Kim [64] analyzed photographs captured by smartphones to match skin and hair colors with clothing for each person. The fabric color classifications were demonstrated in the case of woven and batik clothes using smartphone colorimetry [65], [66].

3.5. Smartphone-based microscopes

In addition to conventional scanning and photographing, smartphone cameras are increasingly implemented as platforms for microscope imaging. Since mobile phone cameras could capture micrographs from the eyepiece lens of a microscope, portable microscopes have been developed by attaching optical components to the smartphone [67]. Compatible with conventional microscopes, a light source to irradiate a specimen at a high incident angle and an external lens are incorporated. A translation stage is also required for focusing and depth adjustment. The developments of smartphone-based microscopes until 2016 were summarized by Contreras-Naranjo *et al*. [68], and Ayardulabi *et al*. [69] focused on their applications in point-of-care systems. The detection of specific cells, molecules, and microorganisms shown in [69]–[71] could be implemented in practical operations. The image storage and analysis then enable facile and cost-effective telemedicine diagnosis in rural or remote areas.

Interestingly, some smartphone-based microscopes have been set up without an external lens, and the detection limits as small as 0.5-2.2 micron were achieved [47]. One method is to capture direct shadow images under ambient illumination and reconstruct images taken at varying angles by a computational algorithm [7], [72]. Computational algorithms empower recent smartphone microscopes with the additional target recognition ability. Machine vision and deep learning have been incorporated in microscope image analysis, as exemplified in [73], [74]. Spatial resolutions of computational smartphone-based microscopes are also enhanced. ‘CellScope’, an example of such developments, has a resolution of around 5 microns and can be used for brightfield, darkfield, and phase-contrast imaging [75]. These three modes could also be operated in the color-coded light-emitting-diode microscopy (cLEDscope) [76]. Imaging of several biological specimens consists of the illumination from an LED array, image decomposition according to the RGB color space, and image computation [76].

Different add-ons and filters were needed to turn a smartphone into a fluorescent microscope of higher sensitivity [77]. Red and white blood cells were successfully discriminated [78]. A higher resolution was achieved by ultraviolet surface excitation [79], and imaging of nanoparticles and fluorescent viruses was enhanced by the surface fluorescence from thin metallic films [80]. Self-assembled nanoantenna also successfully boosted fluorescence signals in visualizing a single molecule [81]. Besides, bioluminescence was observed on a smartphone [82]. In addition to microscopes, some unique experiments were reported. Lincoln [83] designed a lesson on mirrors and shutters as well as simple eye testing based on a smartphone without an additionally downloaded program. Colicchia and Wiesner [84] studied photographs of the retina inside the eye through the pupil.

4. PROSPECT AND CONCLUSION

Smartphone sensors and apps have greatly been developed to serve in scientific measurements. Microscopes, colorimeters, spectrophotometers, goniometers, and magnetometers based on smartphones are successfully implemented for portable and cost-effective uses in STEM education, environmental studies, point-of-care diagnostics, home-based health monitoring and rehabilitation. Since access to any laboratory may be limited during the pandemic, these smartphone-based instruments provide alternatives with comparable precision and accuracy to traditional equipment. Any smartphone is an inherently communicating, controlling hub, and well supported by other systems. It follows that a wireless sensor network and a network in citizen science activities can conveniently be organized. The obtained data can then be mapped with the geographical regions using the GPS unit. It bodes well that the ability in data management is enhanced, whereas sensors’ power consumption is decreased. The combination of data measuring and processing will fulfill the potential of smartphones as smart tools.

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