Smartphone Optical Sensors

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Optical add-ons and apps that take advantage of smartphones' connectivity and computing power are opening up opportunities in education, food safety, health care and environmental monitoring.


Getty Images

Smartphones and wearable devices empower much of our everyday lives, providing driving directions, offering organizational help and facilitating social connections. The integrated sensors in these devices allow tens of millions of people to use them for monitoring their health by tracking physical activity, heart rate and sleep. The optical sensing of the phone's high-resolution camera offers a link to GPS tagging for in-situ mapping, and to cloud-based computational power to run complex analysis.

These examples only hint at the potential of the smartphone as an optical platform, for education, health and science. Here, we look at some of the applications that smartphone optical sensors are enabling—both via the phone's onboard camera, and through the addition of new sensors to the platform.

Leveraging the onboard camera

A large class of smartphone-based optical applications use the smartphone camera directly as an optical sensor. The combination of smartphone-based microscopes and telemedicine across mobile phone networks, for example, has the potential to be a game-changer in low-resource countries, where a lack of training, funds and portable equipment can otherwise make the benefits of microscopy for disease diagnosis inaccessible.

As a case in point, the research group of OSA Fellow Aydogan Ozcan at the University of California, Los Angeles, USA, has developed a lensless microscope based on holographic digital imaging using light scattering, and has followed that up with many point-of-care diagnostic tools to take advantage of the camera, screen and computing power of smartphones. Other researchers have tested smartphone-based, label-free biosensors that measure spectral changes in reflected light of a photonic-crystal chip or surface plasmon sensors, as well as paper-based microfluidics integrated with smartphone-camera-based for point-of-care diagnostics.

While researchers have come up with many interesting optical applications in the lab, actual commercial applications have been few and far between. Daniel Fletcher's lab at the University of California, Berkeley, USA, along with global collaborators, has designed and developed a mobile microscopy system, CellScope, that uses the phone camera as the imaging device, and that is marketed for health applications including detection of tuberculosis, malaria, parasitic worms and ocular diseases, as well as for cytology, environmental monitoring and education. The group has also commercialized an attachment for imaging inside the ear, which connects to a smartphone and uses an inverse lens to take the video of the eardrum that is sent through an app to an on-call doctor for diagnosis. Another company, D-EYE, has developed an ophthalmoscope smartphone attachment that, in one study, reportedly achieved higher accuracy in clinical descriptions than a direct ophthalmoscope.

Visible and near-infrared (NIR) spectrometers for smartphone have also begun to attract considerable interest. An early demonstration, in 2011, used a grating mounted to the smartphone camera; subsequent demonstrations of spectrometers have featured a variety of transmission and reflection geometries, including spectrometers that employ a piece of DVD as the diffraction element.

Expanding the platform

While using the smartphone camera directly as the optical sensor allows for rapid prototyping and demonstrations, it does create issues for commercialization. The image quality and thus the sensor accuracy depend on the camera quality and, hence, on the specific phone used. Images from high-end phones can be corrected, but this becomes difficult for images from lower-cost smartphones (those selling for US$100 or less). On the other hand, these lower-cost tablets and phones, if they have good computing power and compression, can still send large amounts of data even on 2G networks, which makes them very attractive for telemedicine and education in otherwise underserved areas.

In addition, the infrared filters integrated into onboard smartphone cameras makes them unsuitable for imaging or spectroscopy in the NIR, and thus for applications such as multispectral imaging. Large variations in image quality constitute another major concern; smartphone cameras generally allow very limited control of parameters such as white balance, exposure time and color balance, and parameters such as exposure time and programmable gain tend to be automatically adjusted to prevent under- or overexposure. Likewise, most smartphones automate image post-processing functions like edge sharpening, compression and noise reduction. All of this creates barriers to quantitative image analysis and spectrometric analysis.

Finally, the smartphone industry moves very fast, with new devices appearing every few months and with dimensions and feature sets continually changing. This

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creates another barrier for commercialization, as the accessories needed to attach specific optical elements to the phones likewise are always in flux. (D-EYE's product, for example, is still compatible only with the iPhone 7—three generations behind.) And the physical requirements that tie a product to a specific smartphone increases the cost of the accessories, undermining the promise of low-cost applications.

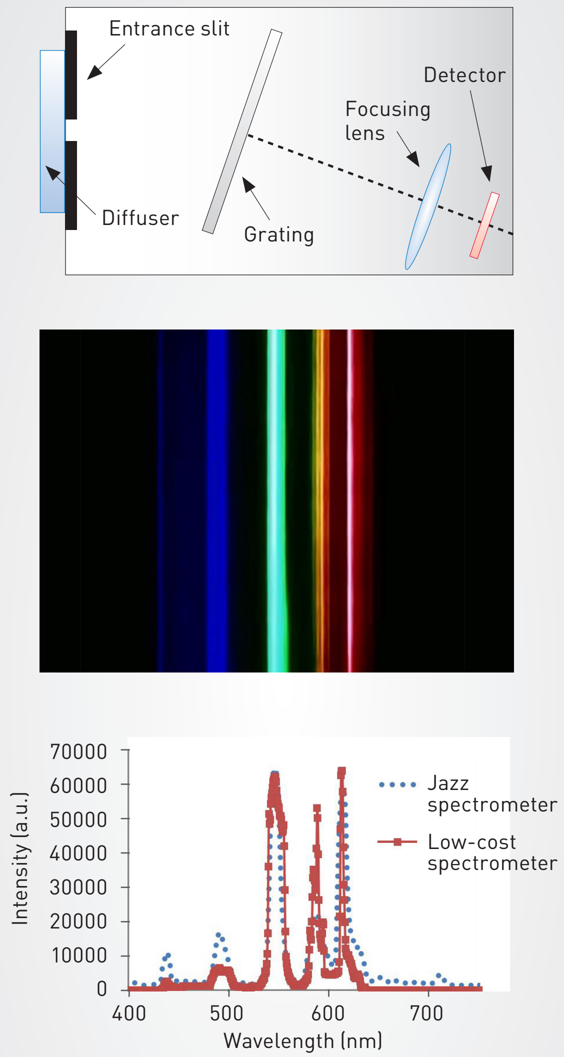
Our group has focused on a different approach to building sensors integrated with smartphones and tablets—one that takes advantage of the platform's computing power, connectivity and energy storage for driving the sensors, while integrating a camera as the optical sensor. An 8-megapixel or better smartphone camera with an autofocusing lens, more than adequate for most applications, can be sourced for US$6–$10. Using cameras that are one generation behind those of market leaders can keep costs low, and also provides the standardization that allows additional sensor devices to work across a range of smartphones and tablets.

In the rest of this article, we describe some of the optical devices and applications on which our group has focused using this technique—particularly in the areas of education, sensing for food and water quality, and sensing for healthcare and telemedicine.

Optical mobile platforms in education

Smartphones provide a great opportunity to increase young people's interest in STEM subjects, and especially in optics and photonics. In recent years, we have tested an immersive learning experience at a local elementary school in Waterloo, Canada, in which children from grades 4 to 8 are introduced to optics technologies while trying to solve real-world problems.

One such activity involves a competition to build the best water filter. A key question is how to measure the water quality and thus judge the filter quality; this inevitably leads to using light, either through optical microscopy or through color. Children begin to interact with light and colors at a very early age; thus teaching them about properties of light becomes exciting and natural, and interest has grown in teaching



A smartphone-based spectrometer

A simple, 3-D-printed sensor design for smartphone attachment (top) provides both dispersed spectral images, such as one for a compact fluorescent lamp (middle) and detailed spectral data that compare favorably with the signal from a commercial instrument, the Ocean Optics Jazz spectrometer (bottom).

I. Khodadad et al., ETOP 2015, paper 9793-104 (2015) spectroscopy at various educational levels, with learning judged to be particularly successful when students do the experiments themselves.

Educational spectrometers available today cost from a few hundred to a few thousand U.S. dollars. The Vernier SpectroVis Plus, for example, with a spectral resolution of 4 nm (FWHM at the 656 nm spectral line), costs US$661, and the nonprofit company Public Lab has developed low-cost DIY spectrometers based on a folded cardboard housing. The diffraction element in the Public Lab device is a small piece of DVD, with the housing taped onto a smartphone camera to do the measurements. Students can print the housing on paper, and then cut and fold it to hold the grating.

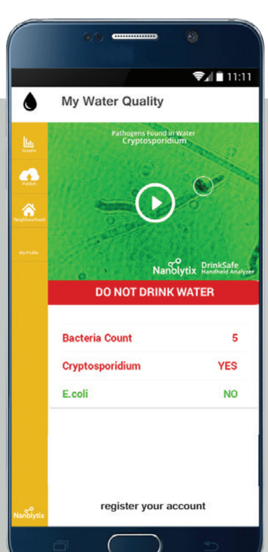
The Public Lab spectrometer can be used to measure the spectrum of various light sources, but not much beyond that. Thus, our group has developed a low-cost spectrometer kit that uses holographic transmission grating as the dispersion element, and an 8-megapixel, externally mounted camera with autofocusing lens—similar to those used in smartphones, but with the IR filter removed. A 3-D-printed housing allows students to assemble the spectrometer on their own. The slit consists of two razor-blade cuts spaced approximately 100 microns apart and already fixed in the 3-D printed housing. A USB cable connects the camera to the smartphone or a tablet, providing both power and a data connection. An app on the phone or tablet shows both the dispersed color image and the resultant spectra. Seeing dispersed colors is always exciting for young children, and allows an easy and intuitive frame of reference with rainbows.

From white light to fluorescence measurements

Future improvements will add spectroscopic techniques that will allow calculations to be done within the app itself. The spectrometer is built modularly and allows for reflectance spectroscopy with broadband LEDs, mounted at 45 degrees around the slit to shine light on the sample and allow reflection spectra for solid samples like fruits and vegetables. For measuring liquid samples, a module can be mounted onto the spectrometer that has a cuvette holder and a broadband white LED for transmission measurements, and a green LED and a red laser for fluorescence measurements. The spectra obtained compare well with those from a commercial spectrometer.

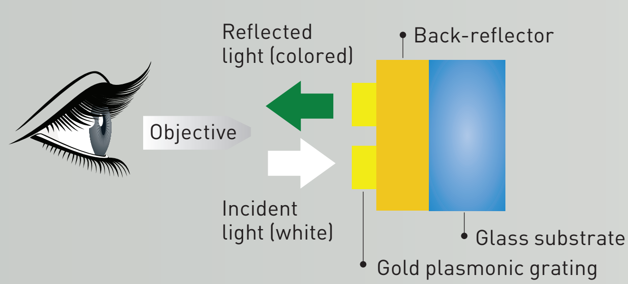
Our experience suggests that the smartphone spectrometer kindles natural curiosity in young students—curiosity that we believe could lead to enhanced interest in optics in the long run. One interesting experiment involves measuring different "white" light sources like halogen lamps, xenon flashlights and LCD screens; this naturally leads to a discussion of CIE color spaces and our perception of color (see "Color vision and color spaces," OPN, January 2019, p. 44).

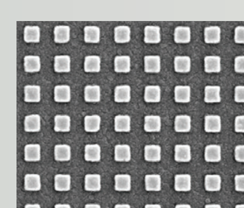
Fluorescence measurements also provoke a strong response; kids generally have exposure to phosphorescence through glow-in-the-dark clothing or other materials, and thus latch onto fluorescence and its potential for scientific study very quickly. The use of fluorescence is demonstrated in olive oil, and students are then given the spectrometer to experiment on their own and report their findings. Students have used the spectrometer in exercises such as measuring oil slicks



Smartphone imaging for water safety

The Nanolytix system uses a nanophotonic chip on which color changes, owing to surface plasmon resonances, can be used to detect the presence of contaminants.





SEM image of the chip (Scale bar= 1 μm)

Nanolytix / Adapted from M. Khorasaninejad et al., IOP Nanotech. **24**, 35501 (2013) / Getty Images

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near grates, assessing color generation in LCD screens and detecting decayed meat—with some experiments well beyond what we originally envisioned.

Testing for water safety

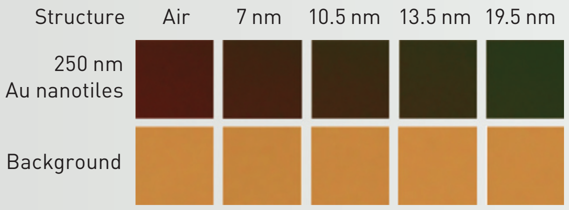
Outside of the classroom setting, our group has also been working on developing smartphone-based optical sensors for ensuring food and water safety. The water sensors are being commercialized through a startup company, Nanolytix. These sensors could help address a potentially serious need—with the world population now greater than 7 billion, providing safe water and food at low cost and high efficiency, and with a reduction in waste, has become a major concern.

On the water side, the global testing market has been estimated at US$2.7 billion in 2014, with a projected compound annual growth rate of 5.2 percent from 2014 to 2019 and an expected annual market value of US$3.6 billion by 2020. Among the reasons for the strong, consistent expected market growth are increased government regulations for water quality; environmental concerns about contamination and pollution; global water shortages, which increase the value of clean, fresh water; and increased industrialization and urbanization, which has created a greater demand.

At present, water sensing requires extensive sample preparation and lab facilities. Photonic sensors such as surface plasmon sensors or ring resonators promise lab-on-a-chip applications, but these sensors require either tunable lasers or high-resolution spectrometers, which increases the cost of the system.

Our group has developed a low-cost sensor that changes color in the presence of a detected contaminant. The sensor uses a 2-D plasmonic periodic nanostructure on a conducting substrate, which results in interaction of the localized surface plasmons and reflections from multiple boundaries to create a highly sensitive detector. The interaction also creates structural colors, which change as the plasmon resonance shifts in the presence of detected substances. Thus the sensor can be illuminated with a white LED, and the sensing measurement accomplished by taking a picture with the camera.

The sensor is powered by a smartphone, which also includes image analysis software to analyze the results. The system can achieve single-molecule detection with only a smartphone camera. And the nanophotonic chip also highly localizes the electric field at the top surface of the sensor, resulting in a highly surface-enhanced Raman signal (2 to 10 million analytical enhancement factor). Our group is now working on building low-cost Raman spectrometers with camera sensors to allow for a fully integrated multimodal sensor system.



Experiment showing the different color changes when different thicknesses of SiO_2 were deposited on the chip.

A prototype of a tablet-based multispectral retinal imager.

Compact multispectral for food safety

Multispectral and hyperspectral imaging in the NIR (700 nm to 1100 nm) and shortwave infrared (SWIR, 1100 nm to 2200 nm) regions is useful in detecting contaminants and defects in food and in quantifying food constituents. NIR spectroscopy also can measure biochemical properties of food and is being tested by retailers to check the quality of incoming produce. Multispectral imaging traditionally requires a combination of an imaging device with a filter band, such as a filter wheel, or some form of tunable filter, or a combination of many imaging devices with various spectral-beam-splitting optics. As a result, in spite of many potential applications for multispectral imaging, most of the commercial systems available are expensive (with costs above US$20,000), bulky and complicated, which has limited their real-world use.

Multispectral imagers developed by our group for detecting freshness and quality of different produce offer a lower-cost way to apply these techniques to food quality. These devices measure multiple wavelength channels in the visible and near-infrared wavelength regions. The channels are optimized to pick up different chlorophyll absorption peaks and absorption peaks for water content, sugars, internal bruises and other parameters. The multispectral imager sequentially lights up the produce with different wavelengths and takes the image with a monochrome machine-vision camera. The images are sent to a tablet or a computer via a USB connection, where they are analyzed in artificial neural networks and the produce's shelf life is estimated. The smartphone thus, in this case, functions as a decision support system allowing image analysis and task tracking, alerts and red flags.

Our group is also working on a device that uses sequential multispectral imaging for retinal fundus imaging—with a key market being telemedicine in India, the country with the largest population suffering with eye diseases. A point of departure for this development is work by the research team of OSA Fellow Vasudevan Lakshminarayanan at University of Waterloo to develop artificial-neural-network-based classification of glaucoma by segmenting the optic disk and optic cup in the retinal fundus image. One problem, however, is that blood vessels and nerves in the fundus image sometimes obscure other features of interest. Multispectral imaging can overcome this by progressively imaging different layers of the retina and the choroid.

Although portable retinal imagers are already in clinical use, multispectral imaging is available only in very expensive, benchtop devices. The device we

Multispectral measurement of internal and external bruises in bananas in two different IR channels images external bruises, including four superficial notches on the banana skin (center), and internal bruises (right) on a banana. As the right-hand image shows, the banana meat is decayed at the bottom and the top. Left: Getty Images

These applications only hint at the promise that's emerging in integrating optics with smartphones for building sensor-driven applications.

are developing for this application uses the same principles as the food sensors: LEDs illuminate the retina at different wavelengths, and a camera captures the resulting images. The camera links up to the low-cost Datawind Ubislate tablet for visualizing the images and allowing the user to focus the camera to the retina, using an NIR wavelength for focusing to avoid constricting the iris. Once focused, the camera rapidly takes images at different wavelengths and sends them to the tablet, which performs initial, relatively crude image processing and composition, and to a cloud server, which does more complete processing and AI-based classification.

Ultimately, the aim of the device is to allow retinal images to be captured in rural settings, with initial diagnosis done through cloud-based AI (to prioritize patients based on clinical need), followed by clinical expert diagnosis of the images in a tertiary center.

An enabling future

In this feature, we have focused on a few applications being pursued in our own lab. These applications only hint at the promise that's emerging in integrating optics with smartphones for building sensor-driven applications. Commercial devices using the camera, computing power and connectivity of mobile devices have started to materialize, with performance matching that of some laboratory instruments—enabling previously undreamed-of applications in areas such as quality control, health care and environmental sensing.

Low-cost, smartphone-integrated sensors can also bring optical sensing to the masses—as demonstrated by the success of efforts such as the iSPEX citizen-science project in Netherlands, which used smartphone-based sensors to measure atmospheric aerosol concentrations. Currently, most devices rely on add-on accessories that use the hardwired smartphone features. As different applications develop and as smartphone manufacturers seek to differentiate their products, however, spectral channels will likely begin to be integrated within the smartphones themselves.

When that happens, consumers may be able to use their smartphones, out of the box, to monitor food quality, avoid food wastage and food poisoning, detect for adulterants, monitor air and water pollution, and leverage other knowledge to improve their wellbeing. Further increases in computational power will allow smartphones to run edge AI algorithms for image analysis on the smartphone itself. And our initial work suggests that low-cost smartphone-based sensors can ignite interest and curiosity in optics and photonics among students at an early age. We indeed live in exciting times. OPN

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