TND415/D

Optical Sensors in Smart Mobile Devices

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TECHNICAL NOTE

Abstract

Smart mobile handheld platforms continue to integrate an ever increasing spectrum of functions from multiple communication standards to a wide array of user interface features and sophisticated power management. This paper explores advances in optical sensors as they apply to enhancing the user experience and extending battery life. Developments in ultra-low power optical proximity sensors are enabling distance measurement and contactless gesture detection while simultaneously supporting novel power management techniques. Integration with traditional ambient light sensors optimizes display power while maintaining satisfactory illumination.

THE MOBILE POWER BUDGET

Advances in smart mobile devices seem to occur on a daily basis as vendors roll out new models and new features. These advances are enabled and fueled by corresponding advances in the underlying silicon technology where Moore’s Law continues to operate. Moore’s Law advocates a doubling of integrated circuit components per unit cost every year [1].

Moore’s Law assumed power consumption would be a non-issue. It is true that from one process generation to the next power consumption for the same on-chip feature is improving. However, any power savings are quickly consumed as even more features are added to the smart mobile devices. And most real world interfaces, such as the intensity requirements for backlit displays, are driven by human eye capabilities. Significant power improvements in backlighting are not expected in the near future.

Battery technology does not track Moore’s Law. Battery technology is estimated to improve at the rate of about three percent per year [2] which equates to a doubling of performance on a 25 year cycle. Batteries are simply not keeping up with silicon technology as can be clearly seen in Figure 1.

The drive to add more features and limitations in battery technology has caused designers to turn to silicon technology to find innovative ways to reduce power consumption and extend battery life.

The best way to conserve power is simply to turn off the power switch. For power hungry display back lights, the trick is to keep the back light off as much as possible without annoying the user. There are multiple strategies, such as detecting when a flip-cover is closed, when the device is in a holder or if the user hasn’t touched the screen for some amount of time. A more recent development is to detect when a device is being used in a manner where the display does not need to be lit, such as holding a phone next to the ear.

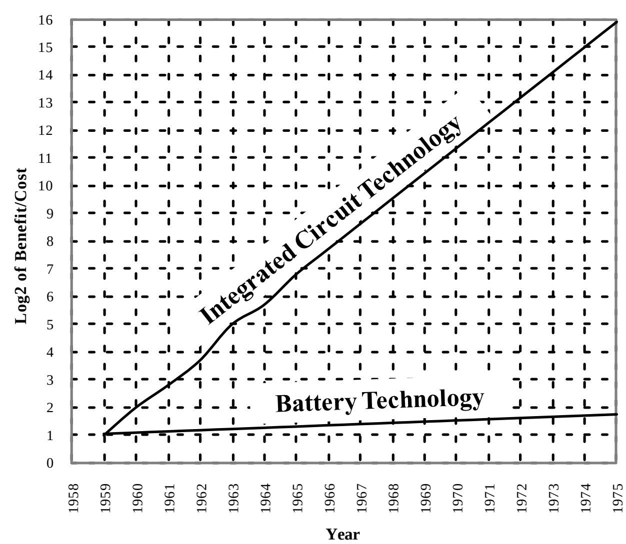

Figure 1. Moore’s Law and Battery Technology

When power is needed, the next level of optimization is to minimize consumption. For backlit displays, this means reducing the lighting level to the minimum acceptable level. Obviously in a dark room, the display can be dimmed significantly with considerable power savings. However, that illumination level will be completely inadequate for sunlight conditions.

OPTICAL PROXIMITY SENSORS FOR POWER MANAGEMENT

Proximity sensors have been used for years in industrial applications, particularly in manufacturing process lines to determine when a production unit is passing by. The most basic sensors use a light interrupter approach which shines a beam of light to a photo sensor on the other side of a path or belt. More sophisticated sensors reflect light off the target product back to a photo sensor located near the light source. This approach can be categorized as a near-far detector as it can detect when a product is close to the sensor.

This same near-far proximity sensor technology is being applied to smart mobile devices. In its most basic form, a proximity sensor can replace a mechanical switch to determine when a flip-lid or keyboard tray is closed. It can also be used to detect when a phone is held close to the face.

Industrial proximity sensors typically use visible light which might not be so desirable in smart mobile device applications. We certainly don't want the proximity sensor light source to expend more energy than we are saving. These concerns are addressed in mobile devices by shifting from the visible light spectrum to the near-infrared band and by shifting from a continuous measurement system to a sampled measurement approach. The visible light spectrum runs from 390 nm to about 750 nm wavelength. Infrared (IR) LEDs commonly used in remote controls are available in the 875 nm near-infrared (NIR) range which is just outside the visible band and is clearly distinguished from the 10,000 nm long-wavelength infrared band which we sense as heat.

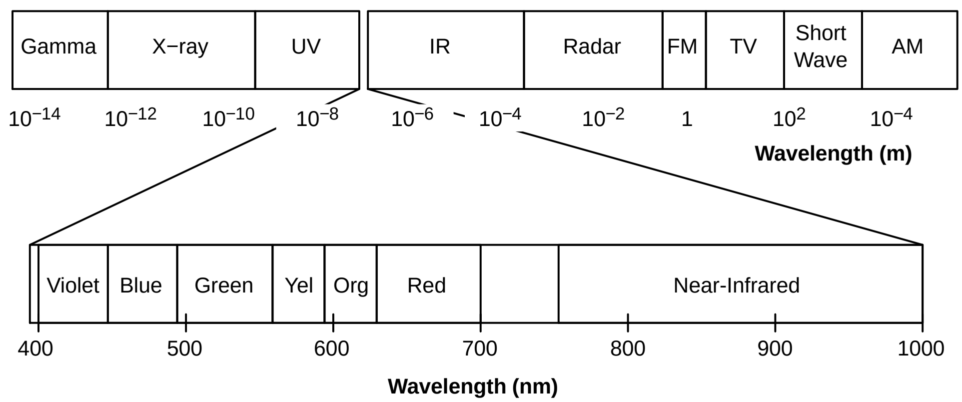

Figure 2. Visible and NIR Light Spectrum

Silicon photo-diodes have a broad spectral response as shown in Figure 3 which includes both visible light and the near-infrared band making them useful detectors for LED generated light. To make a useful proximity sensor it is desirable to filter both visible and infrared light outside the LED's band. Any light not generated by the LED is considered as background noise. The sun and incandescent and fluorescent lights are significant sources of near-infrared radiation. It is not uncommon for these noise sources to be brighter than the LED.

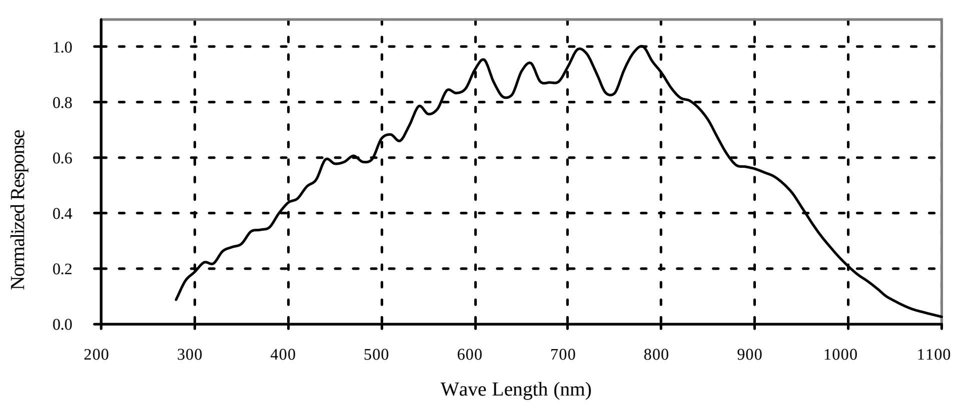

Figure 3. Silicon Photo-Diode Spectral Response

Various filtering approaches exist, including the application of optical filters. In addition to optical filters, another very effective approach is to pulse the LED at a relatively high frequency and apply a high-pass filter to the photo-diode signal. This has the added benefit of reducing LED power consumption.

A useful and effective near-far proximity sensor can be achieved as shown in Figure 4 by shining a pulsed IR LED at the target and then sensing the reflected signal through an optical filter to a photo-diode driving a high-pass filter. By sampling and integrating this signal, it is possible to determine if the target object is near or far away. If the system is properly calibrated and the reflectivity of the target is known, then the actual distance can be computed. In smart mobile device applications, the reflectivity may not be so well known with variations in skin tone, hair color and the possible presence of jewelry. In practice, color tones to the visible eye have little direct correlation to IR light reflectance. Never-the-less it is difficult to know a-priori the precise reflectance of the target, but assumptions can be made to create a useful near-far sensor.

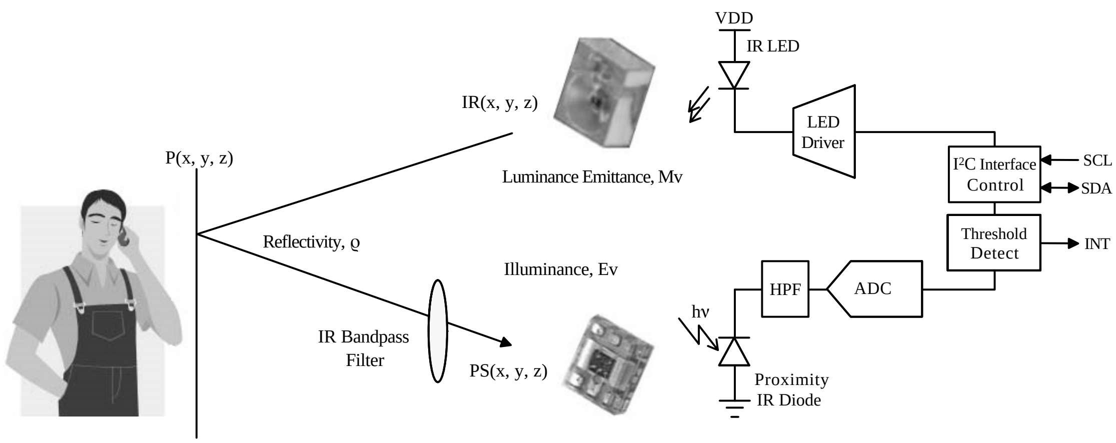

Figure 4. Near-Far Proximity Sensor

With a near-far proximity sensor in hand it is possible to add sophistication to the power management system to turn off the display back light when the phone is held near the ear. It is also possible to switch between speaker-phone and hand-set volume levels, or even provide some degree of volume control as the phone is moved closer or farther from the ear.

Several types of proximity sensors are available. The analog proximity sensors typically use an external resistor to set the detection threshold and a second external resistor sets the LED drive current.

Digital proximity sensor devices are generally more sophisticated with an analog-to-digital converter and some DSP processing to filter the signal and provide various threshold detection options controlled via an I^2C-Bus interface. The proximity sensor readings can be accessed over the I^2C interface and typically an interrupt pin is provided to provide a simple near/far output signal.

The power levels used to drive LEDs in proximity sensor systems for mobile applications are extremely small and the amount of light received at the sensor is greatly attenuated by distance. Therefore the sensitivity of the receiver is an important characteristic.

AMBIENT LIGHT SENSORS (ALS) FOR POWER MANAGEMENT

As we’ve already seen, the silicon photo-diode provides broadband response to visible and NIR light. Properly harnessed in an ambient light sensor, this capability can be used to dim the backlight and achieve additional power savings.

Because of the wide spectral response, there is a potential issue with false-positive light readings. This could occur in a dark room with an IR light source which would cause the sensor to read a high light level thereby driving the backlight to full intensity. The ideal situation is for the ALS to mimic “photopic” human eye light response as shown in Figure 5. Photopic light response can be crudely approximated by subtracting the ambient reading from the proximity sensor with its IR-pass filter and from the ALS sensor reading. A much more accurate method is to apply a photopic optical filter to the ALS photo-diode.

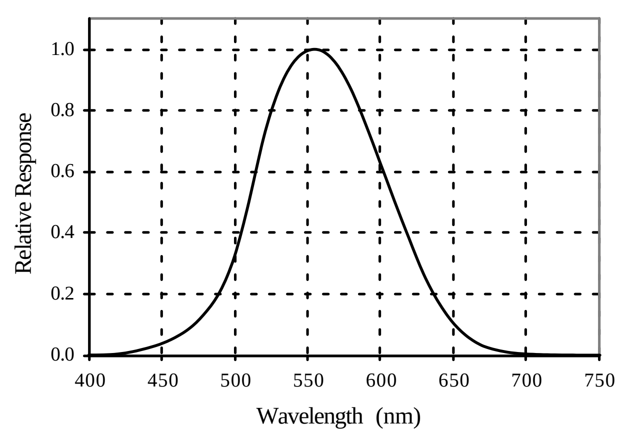

Figure 5. Photopic Light Response of the Human Eye [3]

Table 1. APPROXIMATE AMBIENT LIGHT INTENSITY LEVELS

Light Source	Illuminance (lux)
Direct Sunlight	100,000
Full Daylight	10,000
Overcast Day	1,000
Office Lighting	500
Office Hall Lighting	100
Family Living Room	50
Twilight	10
Deep Twilight	1
Full Moon	0.1
Quarter Moon	0.01
Starlight	0.001
Overcast Night	0.0001

ALS devices exist on the market which cover the light intensity range of a few lux to over 65K lux. This matches well with common ambient light conditions listed in Table 1. While full sunlight is in the 100K lux range, the difference from 65K is insignificant in practical terms. The most useful ALS range is in the 1 to 1,000 lux range with 1 lux resolution at the low end.

ALS devices have seen use in smart mobile devices. However, it has been popular to hide the device behind the dark glass region of the screen which reduces the amount of incident light by up to 90 percent. This shifts the desired ALS sensitivity range downward to the 0.1 to 100 lux range with 0.1 lux resolution.

Silicon photo-diodes generate photo-current each time a photon hits the PN junction. However, they also generate a small amount of current due to thermal noise sources in the silicon. At normal light intensity levels, this is not noticeable. However, in dark conditions it can be substantial and this so-called dark-current can lead to a significant measurement error. ALS manufacturers have developed various compensation approaches as shown in Figure 6. Dark current compensation is a key consideration in selecting low-lux ALS devices suitable for use behind smoky glass.

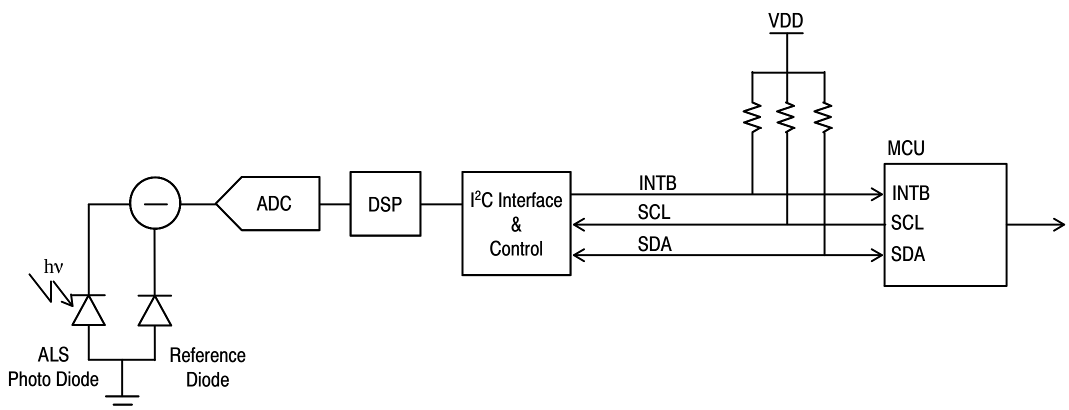

Figure 6. Dark Current Compensated Ambient Light Sensor

How much power can be saved as a result of backlight diming with an ALS? Figure 7 shows the relationship between ambient light conditions and the relative display luminance or brightness. Assume the LED back light consists of a string of white LEDs driven at 50 mA for satisfactory illumination at 1000 lux and passable illumination in full sunlight.

For example, assume the average user operates their smart mobile device in a typical office at 500 lux 70 percent of the time, in full daylight 5 percent of the time and in dimly-lit conference room at 50 lux 25 percent of the time (see Table 2).

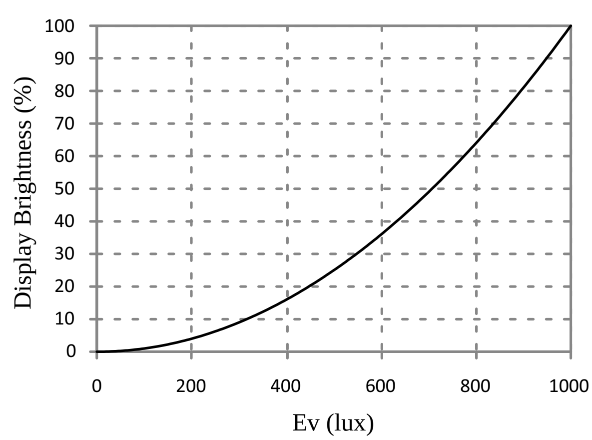

Figure 7. Display Brightness as a Function of Ambient Light Conditions [4]

Table 2.

Location	Display Current	Usage	Total Current
Office	25% * 50 = 12.5 mA	70%	8.75 mA
Daylight	100% * 50 = 50 mA	5%	2.5 mA
Conference Room	0.25% * 50 = 0.125 mA	25%	0.03 mA
Total		100%	11.28 mA

For this scenario, the ALS controlled backlighting power consumption is 77 percent less than a non-ALS controlled device.

A variety of ambient light sensors are available. The analog ALS device typically integrates a photo-diode with a trans-impedance amplifier and some type of dark-current compensation. The output is typically a current source and may be converted to a voltage with an external resistor. Some analog ALS devices include multiple gain ranges to optimize performance in overlapping light intensity ranges.

Digital ALS devices add an analog-to-digital converter and provide the result in a serial data stream. The I^2C interface is widely used as the serial interface to the device. Most digital ALS devices provide a linear binary output of the ADC called the count and provide some means to adjust the count to be equal to lux. Alternatively the adjustment can be performed with a multiply operation in the I^2C host processor.

The human eye has a non-linear response to light intensity. When driving backlighting we would like to account for that response. Some ALS devices produce a logarithmic response which more closely mimics the eye. Square root response has also been shown to be useful. Frequently the linear-to-log or linear-tosquare root conversion is performed in the I^2C host processor either using math computation or by using simplified lookup tables.

INTEGRATED AMBIENT LIGHT SENSORS AND PROXIMITY SENSORS

For smart mobile devices, ALS and PS devices are useful for dimming and completely turning off the display backlight. Both devices are commonly available with the same I^2C bus interface and they both require optical packaging. Why not combine them? An ambient light sensor can be integrated with a proximity sensor without adding any additional pins to the proximity sensing device, resulting in a useful bill-of-materials (BOM) reduction and associated cost reduction.

Some vendors have also integrated the LED device into the package. However, this is not as practical or advantageous as integrating the two sensors. LED devices use much less complex silicon processes and take considerable silicon area compared to the sensors. When combined the LED is constructed in a more expensive process which makes the complete solution more expensive. Also LEDs are manufactured in high volume by multiple vendors for multiple applications and it is challenging to match the economies of scale with a more specialized device.

OTHER PROXIMITY SENSOR APPLICATIONS

So far we have discussed the near-far proximity sensor and its ability to make approximate distance calculations. Let’s take a closer look at the mathematics. Figure 4 shows a light path from an LED to reflector and back to a photo-diode. The light intensity is controlled by the inverse-square law. The illuminance equation for this system can be expressed as follows:

$$E_v = \frac{\rho \, Mv}{\left(D_{IR} + D_{PS}\right)^2}$$

where:

ρ is the reflectivity of the target
M_V is the luminance emittance of the IR LED
D_{IR} and D_{PS} are the distances from the IR LED to the target and from the target to the proximity sensor

We can calibrate the light source and the receiver, and if we know the reflectance of the target we can compute the distance. However, in most applications, the reflectance is unknown, so we have one equation with two unknowns.

If we added a second light path, either by adding another source-receive pair, or by multiplexing in another source or receiver, then we could have two equations with two unknowns. We can solve for the two unknowns and we would know the distance to the target and the reflectance of the target’s surface.

We can extend this farther to locate the relative position of the target. The {x, y, z} position of the target represents three unknowns. So with three light paths we can “triangulate” the target’s position. But again this assumes we know the reflectance of the target.

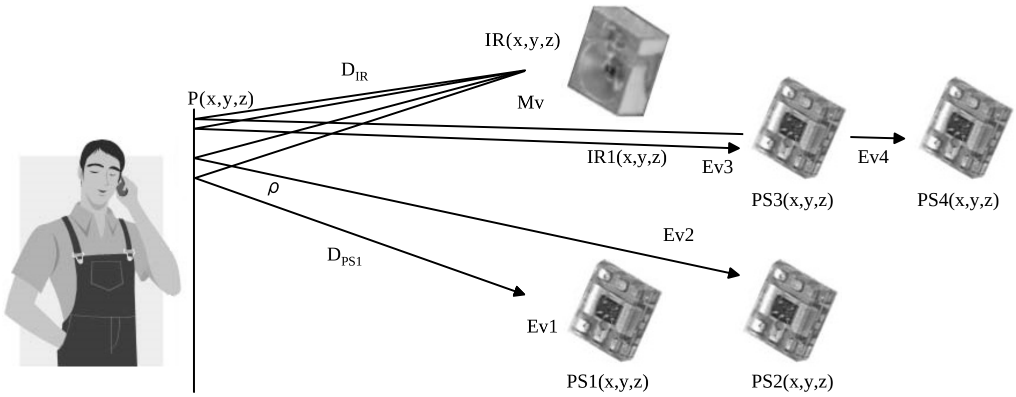

Figure 8. Distance Measurement with Four Light Paths

Adding a fourth light path provides four equations with four unknowns {x, y, z, ϱ}. We can solve for the position of the object and its reflectance.

$$E_{v1} = \rho\, Mv / \left(D_{IR} + D_{PS1}\right)^2$$

$$E_{v2} = \rho\, Mv / \left(D_{IR} + D_{PS2}\right)^2$$

$$E_{v3} = \rho\, Mv / \left(D_{IR} + D_{PS3}\right)^2$$

$$E_{v4} = \rho\, Mv / \left(D_{IR} + D_{PS4}\right)^2$$

$$D_{IR}{}^2 = \left(x_P - x_{IR}\right)^2 + \left(y_P - y_{IR}\right)^2 + \left(z_P - z_{IR}\right)^2$$

$$D_{PS1}{}^2 = \left(x_{PS1} - x_P\right)^2 + \left(y_{PS1} - y_P\right)^2 + \left(z_{PS1} - z_P\right)^2$$

$$D_{PS2}{}^2 = \left(x_{PS2} - x_P\right)^2 + \left(y_{PS2} - y_P\right)^2 + \left(z_{PS2} - z_P\right)^2$$

$$D_{PS3}{}^2 = \left(x_{PS3} - x_P\right)^2 + \left(y_{PS3} - y_P\right)^2 + \left(z_{PS3} - z_P\right)^2$$

$$D_{PS4}{}^2 = \left(x_{PS4} - x_P\right)^2 + \left(y_{PS4} - y_P\right)^2 + \left(z_{PS4} - z_P\right)^2$$

where: x_{IR}, y_{IR}, z_{IR}, x_{PS1}, y_{PS1}, z_{PS2}, x_{PS2}, y_{PS2}, z_{PS3}, x_{PS3}, y_{PS3}, z_{PS3}, x_{PS4}, y_{PS4}, z_{PS4}, are known by design

drive the LED to known M_v

measure E_{v1}, E_{v2}, E_{v3}, E_{v4}

solve for ϱ, x_P, y_P, z_P

Four light paths can be constructed from four LEDs and one proximity sensor, or one LED and four proximity sensors, or even two LEDs and two sensors and proper sensor sequencing. Using fewer LEDs consumes less power.

The discussion so far has made the assumption that LEDs radiate in all directions with equal intensity and that proximity sensors receive light from all directions with equal sensitivity. However the off-axis characteristics of both devices typically vary substantially, which complicates the mathematics and limits the useful coverage space. The coverage space can be expanded by including more light paths over the desired coverage space.

We can make some practical applications by making assumptions about the reflectance and using a three light path system, possibly augmented by more light paths to create a larger coverage space.

The importance of the proximity sensor sensitivity has already been mentioned. For advanced proximity sensor applications, where it is desirable to resolve the position of the target to a reasonable accuracy, the resolution of the proximity sensor also becomes an important characteristic.

GESTURE DETECTION

Many smart mobile devices detect simple gestures made by touching and moving one's finger or fingers across the glass in specific motions. For example, pan can be gestured by sliding one figure in the desired direction. Zoom can be gestured by sliding two fingers either closer together or farther apart.

With optical proximity sensing, this concept can literally be extended into thin air, without touching the glass. With rough triangulation it is possible to determine if one's finger is moving left or right, or from bottom to top, and thus effect a pan gesture. A zoom gesture can simply be moving the finger closer to the screen or farther from the screen. Now we have a really simple 3D pan and zoom gesture system which simultaneously pans and zooms in response to movement of the user's finger over the screen.

Figure 9 illustrates a gesture detection system with three light paths and the corresponding proximity sensor output level over time.

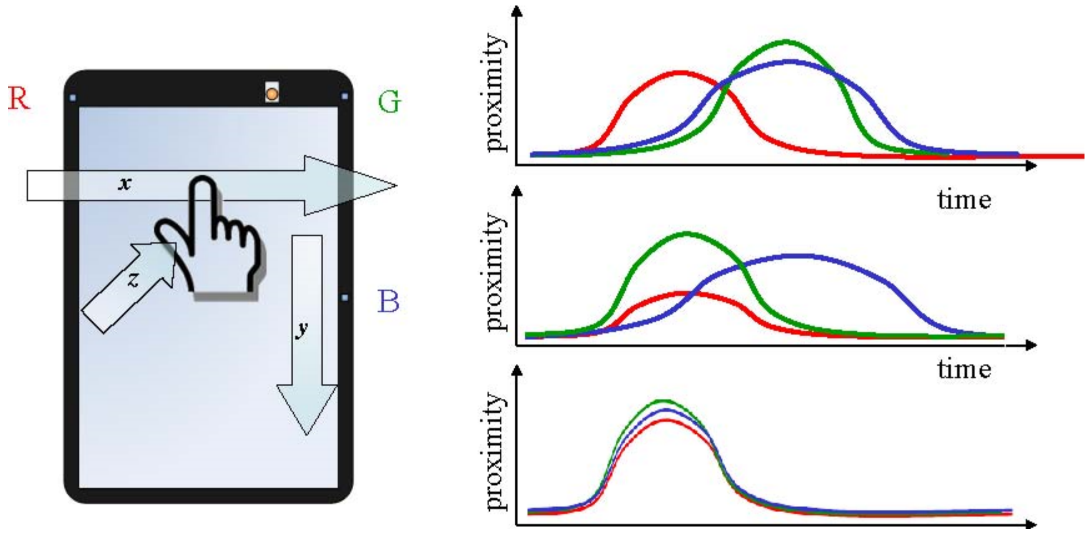

Figure 9. 3D Pan and Zoom Gesture Detection

Other 3D gesture modes are possible as well, including 3D rotation where an object (or the view of an object) rotates left-right and polar south-north in response to finger movement. Zoom could simultaneously be affected by finger height or distance.

Companion gestures can be defined to initiate and terminate gesture modes. For example, wagging one's finger back and forth slightly near the center of the detection space could signal the start of 3D pan-zoom mode. Likewise, wiggling one's finger up and down slightly could signal the start of 3D rotation mode. Wiping one's finger away quickly away to the right (or left or up) could signal an end of the gesture mode.

CONCLUSION

Advances in optical sensor technology are driving improvements in power management and enhancements to the user interface of smart mobile handheld platforms. Integrated ambient light and proximity sensors can significantly reduce power consumption and extend battery life. Multiple light path proximity sensing systems open the door to novel contactless 3D gesture detection techniques.

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