Optical Navigation Systems: The foundation of modern pointing devices

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Optical Navigation Systems (ONS) makes use of optical physics to measure the degree of the relative motion (both speed and magnitude) between a navigation device and the navigation surface. These systems find their major application in pointing and finger tracking devices. Initially, ONS entered the consumer market through optical mice, an application in which they still experience great success. The precision ONS provides in motion sensing, however, has also been found to also make it a suitable candidate for finger tracking applications. This is evident from its widespread use in PC tablets, smart phones, digital cameras, and remote controls.

Optical physics says that whenever a beam of light is incident on a surface, a part of it is absorbed, some of it gets scattered, and the rest is reflected back (see Figure 1). The degree (or the percentage) of absorption, reflection, and scattering depends on both the wavelength of the light and the characteristics of the reflecting surface. The part of light that gets absorbed is practically lost, while the part reflected or scattered can be gathered and processed in order to extract certain amount of useful information.

![Figure 1: Behavior of light while falling on a surface](image-url)
The above facts form the foundation of ONS, as every ONS processes either the reflected light or the scattered light. The techniques used in processing reflected and scattered light are fundamentally different from each other and are discussed separately in the following sections of this article. But no matter how different the processing method is, every ONS contains the following basic building blocks (see Figure 2).

![Figure 2: Basic blocks of an ONS](image)

**1. Optical source**

A variety of optical sources can be used along with the appropriate sensors, including Light Emitting Diodes (LED), and infra red lasers. Laser sources are most commonly used as they provide high resolution and can be used on a wide variety of surfaces, including ones that are somewhat reflective. This can be accounted for the fact that a laser is a uniform light beam which reflects more detail from minor surface defects and textures, even on surfaces where normal LED illumination shows as uniform-color smooth shiny surfaces (like white board). Due to these reasons, devices with laser sources can navigate on surfaces with 20x smaller surface features.

LED’s, though more susceptible to external vibrations and ambient light noise, offer an ease of implementation in applications where high resolution is not required. Compared to LASER sources, LED’s are also not required to meet any eye safety standards. Based on these facts and application requirements, some tradeoffs have to be made when choosing an optical source.

**2. Optical sensor**

In most applications, irrespective of the optical source (Laser or LED) used, a photodiode array is a fundamental part of any optical sensor. However, the arrangement and orientation of the array
depends on the processing technique used and usually varies from sensor to sensor. Each array consists of several tiny photodiodes (pixels) which define the resolution of the sensor. In general, more pixels provide higher resolution.

3. Focusing Lenses

Any ONS is practically impossible without a lens assembly. Focusing lenses are usually required at both the sensor end and the source end. This is required since the apertures near the source and sensor are very small (as small as 1 mm or less). Hence, it becomes necessary to focus the transmitted and reflected light in order to achieve the required precision. The lens assembly is more critical in applications where LEDs are used as a source because they are incoherent and non-directional in nature.

4. Microprocessor unit

For an ONS-based system, the microprocessor unit acts more like a small digital signal processor (DSP). As it receives data from the sensor (photodiode array) in the form of a matrix, analysis is usually complex and requires a DSP. In most systems, the functionality of the DSP and microprocessor is integrated into a single component to reduce system cost and size. Alternatively, some systems use a separate component (navigation engine) as a DSP which communicates with the central processor. Different navigation engines may use different processing techniques depending upon the system’s requirements. Two such techniques are discussed in the following sections of this article.

5. Communication Interfaces

Since every ONS is usually a part of a bigger system, it needs to communicate with other functional blocks of the system. This requires support for external interfaces like USB, SPI, I2C, etc. The most common example is an optical mouse that needs a USB or PS/2 interface to communicate with the PC host. Another example is an embedded application like displacement measurement in robotics and finger navigation in handheld devices, where the ONS needs to communicate with the central processor and the operating system (OS) respectively. This communication usually takes place over I2C or SPI. Optical Mice

Since the most common application of ONS in consumer market is in pointing devices, the following sections talks about its implementation in optical mice.

EVOLUTION OF THE OPTICAL MICE

Early optical mice were first demonstrated in the early 1980’s. Some used an infrared LED and a four-quadrant infrared sensor to detect grid lines (printed with infrared absorbing ink) on a special metallic surface. With this configuration, certain predictive algorithms in the CPU of the mouse were used to calculate the speed and direction of motion over the grid. Other implementations used included a 16-pixel visible-light image sensor with integrated motion detection on the same chip that tracked the motion of light dots in a dark field of a printed paper or a similar mouse pad.
These two mouse types had very different behaviors, as the former used an x-y coordinate system embedded in the pad, and would not work correctly when the pad was rotated, while the latter used the x-y coordinate system of the mouse body. Due to this reason, the former never found much acceptance. With improvements in image (or signal) processing techniques, the second technique has become more and more popular in the field of optical mice. In all modern mice, this signal processing method is what varies. Some of these signal processing techniques are discussed in the following sections.

**REFLECTION BASED METHOD - IMAGE CAPTURE/CORRELATION**

Most existing optical and laser mice use image correlation to determine x/y motion. In this technique, a photodiode grid array forms the required optical sensor. Since the resolution required is not very high, a CMOS image sensor is most commonly used for this purpose. This image sensor captures the reflected light in the form of images of the navigational surface. This image capturing takes place at a very fast rate (as high as 10,000 frames per second in modern mice), while the mouse is moving. Each image is broken into a matrix of pixels and an algorithm is used to find image features in the images. The displacement of the features from one frame to the next, then, represents the motion of the sensor.

In the following example, the change in position of the features indicates that there has been a corresponding change in mouse movement.

![Image correlation](image.png)

As can be seen from the Figure e, Frame 1 has the same features as Frame 2 but shifted down and towards the left. To measure the degree of this shift (i.e., both its magnitude and direction), digital signal processors (DSP) are used. These processors perform a pixel-by-pixel correlation (or in groups of pixels) between the two successive frames, based on which degree of motion is being calculated.
This processing capability of such a DSP is called as the image processing power, and is measured in terms of (Megapixels/sec). This parameter can be calculated for a system by multiplying the total number of pixels in each image (or frame) by the number of images processed per second. Modern day mice can have an image processing power as high as 6 Megapixels/sec. The image processing power is critical for system performance as it directly affects the following quality factors of a pointing device like mice:

1. Resolution, usually expressed in dots per inch (DPI), is directly dependent on how distinctly two successive frames can be distinguished. This distinction is better if more pixels are being processed in a given time period. Hence, higher image processing power is required in order to get better resolution. A typical resolution of a modern day optical mice is 800 – 1200 DPI. It is important to note here that the effective resolution is further affected by software, as the processing software generally implements digital filters for a smoother response.

2. Refresh rate, expressed in Hz or samples per second, refers to how fast the image sensor captures and processes images. To have a higher refresh rate, the image processing power should be high enough to process the required number of frames (images) in a given time period. In general, higher refresh rates are required for higher sensor speeds. Typically, an image correlation-based optical mice has a refresh rate of 10 kHz.

3. Power (or current) consumption of a processor, in general, increases with the image processing power of the processor.

Since the maximum image processing power of a particular processor is fixed, the refresh rate will be lower for higher resolutions. This is quite logical because both refresh rate and resolution ultimately depend upon the number of pixels that can be processed in a given time interval. Thus, a design must balance certain key trade-offs like resolution, refresh rate, and power consumption in order to achieve optimum performance.

SCATTERING BASED METHOD

The scattering based method uses state of the art technology to collect information from the light scattered from the tracking surface (Figure 1). It makes use of “Speckle” – a pattern of light and dark areas (Figure 4), produced by the scattered light. This speckle is generated because of the microscopic textural features of the reflecting surface. Hence, it contains different spatial frequencies that are a signature of surface. Any change in the phase/frequency of these spatial signals implies that the sensor has changed its position. The amount of phase/frequency shift gives information about the direction and magnitude of motion.
In order to analyze such a speckle, a different type of optical sensor is used which has a unique configuration of the photodiode arrays. This configuration is primarily aimed at producing a minimal number of output signals, in contrast to the large number of pixels used in image correlation technique. The reduced number of output signals reduces the processing requirements of the DSP, hence reducing the power consumption and system cost. Different manufacturers use a different configuration in their optical sensors. For example, Cypress Semiconductors’ OptiCheck sensor arranges light sensitive elements in a two dimensional comb detector configuration. The sensor produces only four output signals that completely define the motion of the sensor in x-y plane.

Scattering based implementations have the following key advantages:

Since the number of output signals is considerably less, very high refresh rates (up to 40 kHz) can be achieved. Processing requirements are independent of sensor resolution, which makes tracking speed independent of resolution. This enables simpler and lower cost scaling for products that require both high speed and high resolution tracking performance.

The reduced load on the DSP allows the use of sensors with very high resolution (higher than 3000 DPI), without any considerable increase in power consumption. With only four data inputs to calculate x and y displacement, compared to hundreds of inputs typically required for image correlation, this approach provides for more efficient calculations. This increase in efficiency means that the signal processing blocks have a negligible impact on power consumption, resulting in a system where current draw is nearly independent of speed.

**DESIGN OF A WIRELESS GAMING MOUSE**

Gamers require very smooth mouse operation so as to have realistic movement of their characters in the game. Due to this, a gaming mice design is inherently different from general-purpose mice in many aspects. One such design is presented in Figure 5.
The differences between general-purpose mice and gaming mice, along with certain design constraints on each component are as follows:

1. As compared to general-purpose mice (800-1200 DPI), gaming mice requires a very high resolution (more than 3000 DPI). The optical sensor, whether reflection-based or scattering-based, should be capable of providing such high resolution.
2. Refresh rate requirements are also pretty high (around 40 kHz) as compared to general-mice, which operate at 10 kHz. The navigation engine should be capable of providing such a high refresh rate without compromising power consumption or resolution.
3. The laser driver should properly tune the laser source so as to ensure that the drive levels are within eye safety standards.
4. The wireless interface must provide a high reporting or polling rate (around 1 kHz). This is to ensure that the communication interface does not become a bottleneck when the navigation engine is fast enough to meet the refresh rate requirements. Since the device is meant for very short-range communications, a low power RF interface is required.
5. Since the device is battery-operated, the role of the power management unit becomes critical. It should be intelligent enough to take care of sleep frequency and timing of each component in order to achieve optimized performance with extended battery life.
6. The precision required in interfacing the lens assembly on the board is perhaps the most critical step. Designers must choose a part that is compact and easy to integrate.
7. And lastly, since gaming mice can even have two scroll wheels and five (or more) buttons, it should be taken care that the ADC used has at least 2 channels and the controller has enough GPIO.
After selecting the appropriate components, the next challenge that designers face is the integration of the components. This step considerably affects the time-to-market of a design. For this reason, many designers are moving towards System on Chip (SoC) implementations. As the name suggests, SoC refers to the devices that contain multiple resources on a single chip, including the ADC, laser driver, optical sensor, navigation engine, and power management unit. Some of these resources can be firmware implementations only, while others can be available as ASICs within the chip. Such devices not only reduce the burden of integration but reduce the required board space (and hence the cost) as well.

Devices are also available where even the laser source is integrated. In these devices, the laser output power is calibrated before shipment to meet eye-safety standards and there is no need for laser handling, laser power calibration, or optical alignment. Such integration of laser provides further advantages like increased ESD (Electrostatic Discharge) tolerance of up to 2 kV, compared to only 200 V for standalone lasers.

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