This month, I’ll look at various techniques used for X-ray imaging, from film to modern digital sensors. I’ll also tear apart a CMOS imaging sensor and show how it works. It’s a very different type of radiation sensor than the ionization chamber I discussed in my last column (“Ionization Detectors,” Circuit Cellar 256, 2011). We’ll even have a chance to look at some X-ray images and see just how useful they can be.

The First X-Rays

X-rays have been used to peek inside solid objects for more than a century. It all started in 1895 when Wilhelm Roentgen accidentally discovered a beam of unknown rays emanating from a vacuum tube. He used the beam, now known as an X-ray, to take a photograph of his wife’s hand (see Photo 1). Since that time, X-rays have been used to generate images on photographic film or photosensitized plates in medical, industrial, and other applications. Like other forms of ionizing radiation, X-rays, which are high-energy photons, are harmful to living tissue. Therefore, it’s best to use the lowest possible beam intensity to produce a usable image. But film is not as sensitive to X-rays as it is to visible light. Making the film more sensitive would increase the graininess of the image, reducing its resolution. Instead, an X-ray film holder contains an image intensifier screen made of a special material that converts X-rays to light. With the screen, you need a significantly lower exposure to get the same image as with film alone.

The first time digital imaging was used for X-rays was in the early 1970s, with the development of the first practical computerized axial tomography (CAT) scanner, now more commonly known as computed tomography (CT). It consists of an X-ray tube and an electronic detector at opposite ends of a rotating gantry, with a patient placed in the middle (see Figure 1). Data from the detector is stored as the gantry rotates. The platform under the patient moves slowly (either in discrete steps or continuously in a helical scan system). This forms a series of image slices, which are combined using various mathematical algorithms into a single 3-D representation of the patient’s body. The detectors in CT scanners use the same type of scintillation material to convert X-rays into light as in the image.
rigid. The other end of the cable plugs into an interface module that connects to a computer’s USB port.

Figure 2 shows the key elements of the system. The imaging sensor in this particular unit is a CMOS active pixel sensor (APS) array, though some other products use charge-coupled device (CCD) sensors instead. [Refer to the Resources section of this article for more information on some typical sensors.] CMOS sensors consume less power and can be mass produced more economically than CCDs, which has made them popular in digital cameras. Early development work on CMOS sensors in the 1990s came from research at the U.S. Jet Propulsion Laboratory. They wanted to create a compact, low-power imaging system for NASA for use in deep-space exploration, where minimizing power consumption is critical. At the same time, researchers in Scotland and Sweden were looking to produce a low-cost, single-chip imaging system. The results of these efforts, as well as the steady improvements in CMOS processing technology, gives us the sensors in use today.[1]

There is more pixel-to-pixel variation in the output signal of a CMOS imager than with CCDs, which produces more noise in the raw image data. Most of this is known as fixed-pattern noise that results from manufacturing process variations between the pixels and doesn’t vary from one exposure to the next. The system compensates for this noise, as I’ll explain later. Much of the image-capture logic is contained on the sensor chip, so it can acquire the X-ray image in real-time without any outside help. Since there’s no connection between the sensor and the X-ray generator, it can’t rely on an external trigger signal. There are extra photodiodes scattered in several locations around the sensor that aren’t part of the main image array. These photodiodes are always active, and are used to sense when there is an incoming X-ray beam. This triggers the on-board capture

intensifier screen used for film. Early scanners used a photomultiplier tube to convert the light into electricity, while modern machines use photodiodes.

There is also an indirect digital imaging technique using photostimulable phosphor (PSP) plates. These are flat plates coated with a material that stores energy in areas that are exposed to X-rays. The latent image can be read out by scanning the plate with a laser beam, where exposed areas will emit light when hit by the laser. The scanner can capture the image and store it in a computer. It’s almost like a laser printer in reverse. This technique is also known as computed radiography, since a computer is used to control the scanner, but it’s not to be confused with computed tomography.

Dental X-rays use similar imaging techniques, but on a much smaller scale. When I go for a checkup, my dentist will take a set of intraoral X-rays using small pieces of film carefully placed in my mouth. The X-rays expose the film directly, without the image intensifier screen that’s used in larger film holders. That results in a higher resolution image, since the thickness of the screen enables the light to spread out slightly, providing an image that’s not as sharply focused.

DIGITAL SENSORS

Digital intraoral X-ray sensors were first developed in the 1980s. There have been many technological improvements since then, and many dentists now accept the images from modern sensors as a suitable replacement for film. Photo 2 shows the business end of a sensor. It’s a bit larger than a piece of dental X-ray film, and it’s also more
logic to acquire an image. Once the beam stops, the analog image data is sent the interface module where it’s fed through a 12-bit ADC to a microcontroller and stored temporarily. Once this process is complete, the sensor acquires a second image, this time without an X-ray beam. The microcontroller subtracts this data from the first image to compensate for any fixed-pattern noise in the image sensor.[2] There can also be a gain error from one pixel to the next. Each assembled sensor module comes with a manufacturer-supplied calibration file that is used to adjust the gain of each pixel. The sensor module has a serial EEPROM containing a serial number that lets the computer identify the proper calibration file to use. Once the image data has been processed, it’s stored on the host computer and displayed for the dentist to examine.

Figure 3 shows the construction of the sensor assembly. The top aluminum layer shields the electronics from outside noise, but is thin enough not to interfere with the X-rays. The CMOS sensor will directly respond to X-rays but, like film, it’s much more sensitive to light. The scintillation layer converts X-rays to light so they can be picked up by the sensor. There are several different scintillation materials in use, including thallium-doped cesium iodide (CsI:Tl) and terbium-doped gadolinium oxysulfide (Gd₂O₂S:Tb), also known as Gadox. These are special materials that respond to incoming radiation by producing flashes of visible light.

![Figure 3 - The construction of an X-ray sensor.](image-url)
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whose brightness corresponds to the energy of the radiation. I wasn’t able to find out which material this particular sensor uses, but CsI:Tl appears to be the most common among sensors from other manufacturers. It produces green light with an emission spectrum centered around 550 nm, and is one of the brightest scintillation materials available. It’s also slightly hygroscopic, so it needs to be sealed with a moisture-resistant layer.

Once the scintillation layer produces a flash of light, it’s important to direct it toward the CMOS imager without enabling it to spread out, or the image would become blurry. The fiber-optic plate handles this with a series of vertically oriented microscopic light fibers that are bundled together. It’s glued to the sensor’s front surface and guides light directly to the sensor. The plate also absorbs any X-rays that aren’t trapped by the scintillation layer. This keeps them from reaching the CMOS sensor, preventing them from creating additional noise in the image data. X-rays will also degrade the sensor over time by increasing the sensor dark current and shifting the transistor threshold voltages.[3]

LOOKING INSIDE

Let’s examine the sensor in more detail. They’re a bit too expensive to sacrifice a good one, but I was able to obtain a failed sensor, thanks to Dr. Catherine Brennan, DDS. Photo 3 shows both sides of the sensor assembly. The fiber-optic plate is glued firmly to the sensor. I wasn’t able to remove it, so you can’t see the front surface of the CMOS imager. Photo 3b shows the back of the circuit board. It’s made of ceramic, which is more solid and less affected by temperature changes than a more common fiberglass-based material. Note that there’s very little circuitry needed for the sensor. The two tiny ICs are an RC oscillator and a logic-gate buffer. You can
see several small dark rectangles near the wire connections, which are resistors directly screen printed on the ceramic board with resistive ink. Screened resistors aren’t very accurate unless they’re trimmed, which these don’t appear to be. Here they are used as pull-ups and series ESD protection resistors, where their exact values aren’t critical. Most of the other passive components are 0402 size. I can’t imagine trying to debug a product with parts that small! The far end of the sensor’s cable is attached to a small printed circuit board (PCB) with a row of edge fingers. It just holds some analog and digital buffers, as well as the serial number EEPROM, and plugs into a connector on the USB interface module.

This particular sensor has a 30 mm × 20 mm active area and a 40 µm pixel pitch, giving a resolution of 750 × 500 pixels. Other sensors have pixel pitches as small as 19 µm, but, as with digital cameras, there are so many factors that go into producing an image that it’s hard to judge quality simply from the numbers. You can find other dental sensors with active areas from 24 mm × 18 mm up to 36 mm × 26 mm.

The strain relief on the end of the sensor wire is the most frequent point of failure. That’s not surprising, especially for the smaller sensors that are used primarily in children’s mouths. Some of the newer ones have replaceable cables, and there are even a handful of wireless sensors available that eliminate the problem entirely. But then you need to worry about monitoring signal quality and replacing batteries.

### TAKING PICTURES

Photo 4 shows an image taken with a functioning sensor. You can see that enough of the X-ray beam penetrates the 0.1” thick brass key to show some of the groove detail. If you look closely, you can see a faint vertical stripe near the tip that’s slightly lighter than the rest of the key. That’s a variation in the metal density from when the key blank was formed. It makes it clear how X-rays can be useful to check metal parts for quality or uniformity.

Photo 5 shows the experimental setup. The X-ray generator was set for 8 mA and 60 kV peak [kVp], with an exposure time of 80 ms. The tube current sets the intensity of the beam, which corresponds to the brightness of a visual image. The generator voltage determines the maximum energy of the X-ray photons in electron volts (eV). This corresponds to their wavelength, or the color in visual terms.
wavelength $\lambda$ is given by $\lambda = \frac{1.24}{E}$, with $\lambda$ in nanometers and $E$ in kilo-electron volts (keV). That gives us a value of 0.02 nm for 60 keV. A thin layer of aluminum at the output of the generator blocks any lower energy “soft” X-rays that are produced, since they would be absorbed by the skin and wouldn’t contribute to the captured image.

Typical sensor exposures are about one third to two thirds of film exposure times. The shorter times aren’t a problem for modern X-ray machines, but older models that were designed for film can’t always be set so short. That’s not surprising, since the contact bounce time on the relays used in older machines would likely be a significant fraction of the exposure time. The system used here can be set from 10 ms to 3.2 s, with a tolerance of 5% + 1 ms.\(^6\) The exposure time translates directly into radiation dose, so it’s better to use the shortest time possible that produces an acceptable image. That’s called as low as reasonably achievable, or ALARA. It’s a principle that applies to radiation exposure with a goal of using the minimum dose that will reasonably provide the necessary diagnostic information. In general, the higher the dose, the greater the level of detail in the image. That means there’s a tradeoff between how much information is really necessary, and how much risk that information is worth. In our case, the decrease in dose when going from film to a digital sensor is also accompanied by some loss of detail, since even the highest resolution sensor can’t match the resolution of film. I’ll have to trust my dentist to know whether or not that difference is significant when it comes to looking inside my teeth.

Now that you have a better understanding of what goes on behind the scenes in your dentist’s office, perhaps the next visit will be less scary! \(^5\)

Richard Wotiz has been taking products apart ever since he was old enough to pick up a soldering iron. He’s been helping others put them back together since 1991, when he started his design consulting business. Richard specializes in hardware and software for consumer products and children’s toys. He can be reached at rw601@spiraltap.com.

REFERENCES


RESOURCES

