Shuttering methods and the artifacts they produce

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Abstract

When exposure times were measured in minutes, the opening and closing of the shutter was essentially instantaneous. As more sensitive films and brighter optics became available, exposure times decreased, the travel time of the shutter mechanism became increasingly significant, and artifacts became visible. Perhaps the best-known shutter artifacts are the spatio-temporal distortions associated with photographing moving subjects using a focal-plane shutter or sequential electronic sampling of pixels (electronic rolling shutter). However, the shutter mechanism also can cause banding with flickering light sources and strange artifacts in out-of-focus regions (bokeh); it can even impact resolution. This paper experimentally evaluates and discusses the artifacts caused by leaf, focal plane, electronic first curtain, and fully electronic sequential-readout shuttering.

Introduction

The capture of a properly exposed image requires balancing of the various exposure parameters. Sensitivity to changes in exposure factors in general is logarithmic, so APEX (Additive System of Photographic Exposure) encodes all parameters as log values such that doubling or halving the parameter is encoded by adding or subtracting one from the APEX value of that parameter. The result is that equivalent exposures can be determined by the simple linear equation:

$$Ev = Bv + Sv = Tv + Av$$

The exposure value, *Ev*, represents the total amount of image-forming light. In other words, two exposures are expected to produce "equivalent" images as long as *Ev* is the same.

The values of *Bv* and *Sv* are essentially constants for a given scene and camera. The metered luminance of the scene being photographed is the brightness value, *Bv*. The speed value, *Sv*, represents the light sensitivity of the film or sensor – the ISO. In digital cameras, the value of *Sv* typically is determined by the combination of quantum efficiency, analog gain, and digital gain. However, the quantum efficiency is not easily changed after manufacture, so manipulating the analog and/or digital gain to increase the ISO effectively reduces dynamic range. The remaining parameters, *Tv* and *Av*, are the things that can be directly controlled by the camera for each capture.

The time value, *Tv*, represents the exposure integration period, commonly known as shutter speed even for systems that lack a mechanical shutter. This is the key parameter of concern in the current work. More precisely, the current work centers on characterizing the subtle differences caused by various implementations of shuttering. For example, some shuttering methods give all pixels the same duration of exposure, but do not expose all pixels during the same time interval – thus causing specific types of artifacts.

Figure 1. *Still image from high speed video of leaf shutter*

The aperture value, *Av*, represents the rate of light transmission through the lens. Using a perfect lens, *Av* is determined solely by the aperture *f*/number, which is simply the ratio of the lens focal length divided by the diameter of its circular aperture. However, for real lenses, reflections and other imperfections reduce the light transmitted by a small amount, so it would be more correct to say that Av is determined by the transmission-corrected effective *f*/number, or T/number. The size of the aperture is typically adjustable either using an iris or by inserting a Waterhouse stop, and would seem to be unaffected by the method used to implement *Tv*. However, as the current work shows, the effective aperture size and shape can be changed dynamically during exposure depending on how shuttering is implemented.

The goal of the current work is to experimentally evaluate and discuss how the method for implementing *Tv* – shuttering – produces artifacts in the captured image.

Shuttering Methods

Many different methods have been used to control the exposure integration interval, *Tv*. In the early days of photography, and in some specialized types of modern photography (e.g., using pinholes instead of lenses), exposure integration intervals are so long that nearly any method for removing an opaque cap from the lens to start exposure, and replacing it to end exposure, is effectively instantaneous. For example, the fraction of a second it takes for a human hand to remove or replace a lens cap contributes insignificantly to a pinhole exposure integrating light over minutes or hours. In such a case, there are effectively no shuttering artifacts.

The same claim can be made for *global electronic shuttering*. If a control signal simultaneously resets all pixels and light is integrated until a second signal simultaneously saves the charge accumulated by each pixel, then there are effectively no shuttering artifacts. Unfortunately, global electronic shuttering has proven difficult to implement, and currently almost no consumer cameras employ this method.

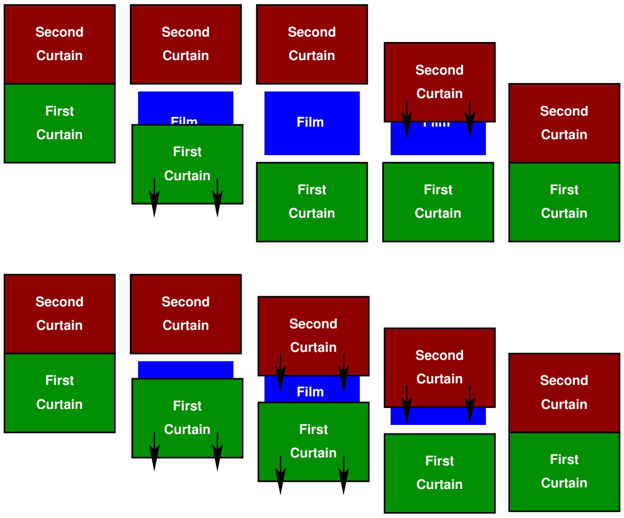


Figure 2. *Low/high speed focal plane shutter operation*

Mechanical Leaf Shutter

Leaf shutters, like the one shown in Figure 1, are very effective as mechanical shutters providing fast shutter speeds in a quiet-operating and compact device. The particular one shown is between the elements of a Kodak Ektar 127mm f/4.7 lens dating from 1948 – and still works perfectly. Leaf shutters employ an iris-like motion in which the blades pull away from the center, hold at a position not interfering with the light path through the lens, and then return to meet in the center. However, an iris is usually designed to keep the path through the lens roughly circular at all times; to reduce friction between blades and thus operate at higher speeds, leaf shutters often create unusual star-like shapes during the open/close process. Because the leaf shutter is typically between the lens elements near the aperture iris, it also can act like an aperture.

Mechanical Focal Plane Shutter

Instead of placing a shutter inside each lens, it can be more cost effective to have a shutter inside the camera body that can be used with all lenses. A mechanical *focal plane shutter* accomplishes this by moving one or more opaque curtains to reveal and then block the film or sensor. The focal plane name is due to the fact that the curtain is placed just in front of, and very close to, the focal plane of the film or sensor. The relatively simple motion of a focal plane shutter also allows for very fast shutter speeds. Very early variants of focal plane shutters were built with guillotine-like panels dropping past the film, and single-curtain versions were famously used in the large-format Graflex cameras, but the modern focal plane shutters found in SLR (single-lens reflex) and DSLR (digital SLR) cameras are generally variations on the dual-curtain type Oskar Barnack used in his 1925 Leica A.

As shown in the left-to-right time sequences of Figure 2, a dual-curtain shutter begins the exposure by moving the first curtain to begin exposing the film. After the desired time interval, the second curtain follows. If the desired exposure integration interval is at least as long as the time it takes for a curtain to traverse the film, then there is some period during which the whole frame of film is exposed – as shown in the upper sequence. The fastest shutter speed at which this happens is called the flash synchronization speed. However, if the desired integration interval is shorter, the film is never completely uncovered and the moving "slit" between the curtains paints the light onto the film over a period of time. Incidentally, the single-curtain variants used a fixed-width slit in a single curtain, but varied how fast the curtain traversed the film.

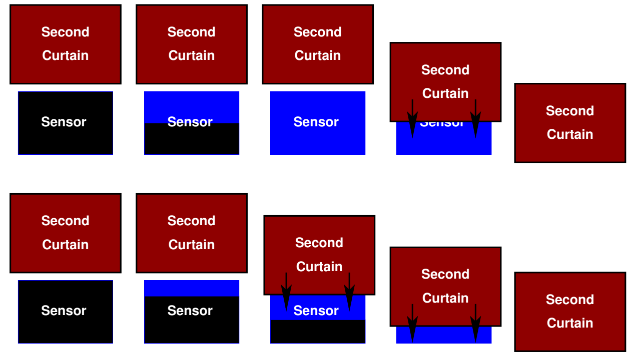


Figure 3. *Low/high speed electronic first curtain shutter operation*

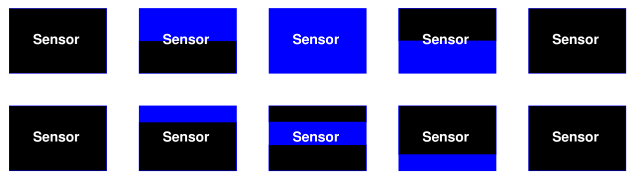


Figure 4. *Low/high speed electronic (rolling) shutter operation*

Electronic First Curtain Shutter

Although dual-curtain focal plane shutters are now available as relatively cheap, highly precise, modules for use in cameras, the design proved problematic for high-resolution digital mirrorless cameras. In SLR and DSLR cameras, the shutter remained closed until the mirror had flipped out of the way to capture an image. In mirrorless cameras, the shutter is normally open to provide an electronic live view. Thus, to initiate an exposure the camera must first close the shutter, then perform the usual focal plane shutter exposure sequence, and finally reopen the shutter to restore the live view. This initial closing of the shutter was found to cause vibration that often slightly blurred the captured image. The solution was *electronic first curtain shutter* – EFCS. As shown in Figure 3, EFCS simply electronically resets pixels in a sequence closely matching how they would be revealed by the first curtain. This not only avoids the mechanical shock of closing the shutter to begin an exposure but can reduce camera cost: for example, the Panasonic Lumix DC-GX850 does not even have a mechanical first curtain.

Rolling Electronic Shutter

Given that sensors in digital cameras can electronically reset pixels, why not have a completely *electronic shutter* operating as shown in Figure 4? In fact, this is precisely what is done to provide the live view in a mirrorless camera. However, although it is

Figure 5. *High speed images of focal plane shutters*

relatively quick to instruct a pixel to reset by dumping any charge it had accumulated, it is generally much slower to read and digitize the charge accumulated. This is a problem because, without mechanically blocking the light, pixels will continue to accumulate charge until their values are read. The result is that electronic shutters are limited to the equivalent of a relatively slow curtain traversal time corresponding to the electronic readout scan rate.

High-Speed Images Of Focal Plane Shutters

Figure 5 presents still frames from 960 frames per second videos of actual shutters of various types as they operated at their minimum integration interval (maximum *Tv* value). The videos were captured using a camera (Sony RX100V) that allowed use of this high framerate with a motion-stopping exposure interval of 1/10000s for each video frame, however, even this high framerate video is subject to shuttering artifacts. The apparent tilt of the shutter blades in most of the images is actually a temporal motion artifact (an artifact discussed in a later section).

The traditional cloth horizontal-run focal plane shutter of a Pentax Spotmatic F at 1/1000s is shown in the upper left of Figure 5 (with a white card in place of film to make the moving slit more visible). This shutter specifies a flash synchronization speed of 1/60s, but the high-speed video proves the curtain traversal time is actually closer to 1/100s. The top shutter speed of 1/1000s is implemented by a slit width of approximately 3.6mm.

The top center image is the shutter of a Canon 5DIV, which is typical of a high-end DSLR in that it employs a rigid-bladed vertical-run focal plane shutter. The quoted flash synchronization speed is 1/200s, which implies a curtain travel speed approaching 5 meters/s. This shutter supports up to 1/8000s (shown here), which means the slit width is approximately 1.6mm. The shutter of the mirrorless Sony A7RII, seen in the top right image, is strikingly similar to that of the Canon 5DIV. However, when it is also set to 1/8000s, the slit width appears to be around 1.2mm, which is slightly smaller than for the Canon 5DIV. This is a surprising result given the quoted flash synchronization speed is 1/250s; it should really be slower than 1/200s.

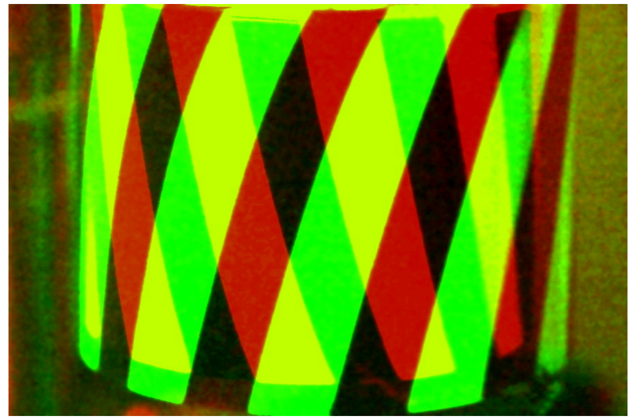


Figure 6. *Rotating drum curtain speed check, A7RII 1/8000s*

The bottom left image shows the same Sony A7RII firing at 1/8000s using EFCS. This is also shown in the bottom center image, but with the high-speed video camera flipped 180 degrees so rolling shutter artifacts point in the opposite direction. The bottom right shows the A6500 firing at 1/4000s using EFCS. Despite a smaller APS-C sensors implying shorter travel, the flash synchronization speed is not faster, but is quoted as 1/160s (which is consistent with the high-speed video). The slit width at 1/4000s is quite small, approaching 1mm. It is useful to note that both Sony cameras tested here expose from bottom to top, which means the top portion of the scene is rendered before the bottom.

The following sections discuss some of the most significant types of artifacts caused by these shuttering mechanisms.

Shading

Even with a fully operational shutter, it is possible that there could be some level of shading (vignetting) caused by uneven movement of the shutter curtain. Photographing a fast-rotating drum marked with alternating black and white stripes provides an approximate measure. If the shutter curtain moves at a constant rate, the stripes should have a consistent angle. Figure 6 combines upright (green) and inverted (red) captures of the spinning drum. The curtain motion is very even through most of the travel, but starts a few percent faster. This is not a large enough variation to be a concern; perhaps variations were often larger with the older horizontal-run cloth curtains?

A more serious shading artifact is the shutter issue probably most discussed by camera manuals: shading caused by EFCS shuttering. Various camera manufacturers either advise against use of EFCS at high shutter speeds or literally disable use of EFCS for high shutter speeds.

Figure 7 shows a series of images of a clear blue sky. Although the lens used (a Minolta Rokkor-X 200mm f/4) imposes some vignetting, the focal plane shutter and fully electronic shutter images shown in the top row are quite evenly exposed while the EFCS image in the center shows heavy vignetting at the top. The Sony A7RII shutter runs vertically, with the second shutter curtain chasing the electronic reset of pixels, but **the two curtains are not in the same plane**. This effectively defines a range of ray incidence angles that cannot pass through the "tilted" slit.

Figure 7. *Shading by focal plane, EFCS, and electronic shuttering*

To confirm this incidence-angle dependence, the top half of the lens was covered so that only rays coming from the bottom half could be sampled. Not surprisingly, this change made only a minor difference in shading using either the focal plane (leftmost image in the second row) or electronic shutter (not shown). As the next image shows, the EFCS response to masking the top half of the lens is far more dramatic: it blocked the only rays passing through the tilted slit for nearly half the image area. Switching to block only the bottom portion of the lens causes about the same level of vignetting seen for the focal plane shutter, but actually helps balance the EFCS vignetting. One could argue that this behavior actually creates a preference for shutter travel direction (which the Sony A7RII wisely uses), because in most scenes more light comes from the top than the bottom.

Despite the EFCS "tilting" of the slit being the dominant shading factor, it is worth noting that the slightly faster initial movement of the curtain (noted at the start of this section) could make this effect slightly more severe.

OOF PSF Shaping (Vignetting) Artifacts

The out-of-focus point spread function (OOF PSF)[1] is the image of a single point of light that was not in focus. The OOF PSF determines the *Bokeh* of a lens: the important, yet qualitative, properties of how OOF regions of the image are rendered. The OOF PSF on an optically perfect lens is an evenly-bright disc matching the shape of the lens aperture. Various lens properties and defects, such as diffraction spots caused by dust specks, are readily visible in the OOF PSF. Surprisingly, the shuttering method can significantly alter the OOF PSF, making bokeh either happily smoother or undesirably more "busy."

Figure 8 shows the OOF PSF measured under identical conditions for a leaf shutter, mechanical focal plane shutter, EFCS, and fully electronic shutter. A custom 3D-printed lens mount was made so that the circa 1948 Ektar lens shown in Figure 1 could be used on the Sony A7RII – and obviously the same lens was used for these four shots, as the diffraction pattern from dust in the lens proves. The leaf shutter image was made by opening the shutter of the Sony A7RII, triggering the Ektar's leaf shutter for the actual exposure, and then closing the A7RII shutter. A brief analysis of the images in 8 follows.

Let's begin with the two shuttering cases that produced the type of image expected: the mechanical focal plane shutter and the fully-electronic shutter. The result is an evenly-lit disc, patterned by diffraction of dust within the lens, and having a sharp edge due to rays being clipped by the aperture of the lens. The electronic shutter image is actually slightly crisper than the one produced using the mechanical shutter. This barely visible difference may be due to slit diffraction (described in the following section) only affecting the mechanical focal plane shutter image.

Most leaf shutters generate a center-weighted brightness variation in the OOF PSF because the shutter's center is open longer than the edges. The bright center is naturally shaped by the way in which the shutter blades open, in this case forming a twisted star pattern. Although the pattern is perhaps disturbing, the shutter behaves as if the aperture size was dynamically changing during the exposure, effectively implementing a form of dynamic apodization. In general, OOF PSFs that have darker edges and a bright center create more visually appealing, smoother, transitions between OOF objects. Thus, it can be argued that **this defect improves the bokeh**.

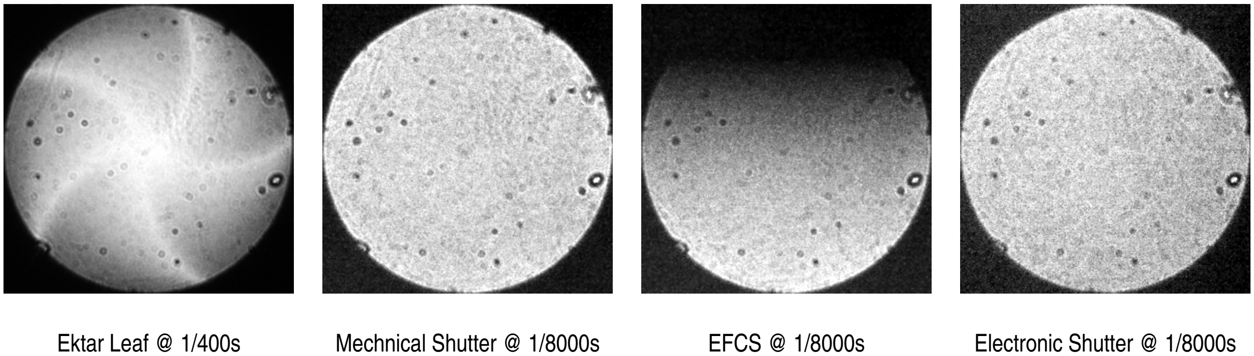


Figure 8. *High shutter speed OOF PSF of Kodak Ektar using various shutter actions*

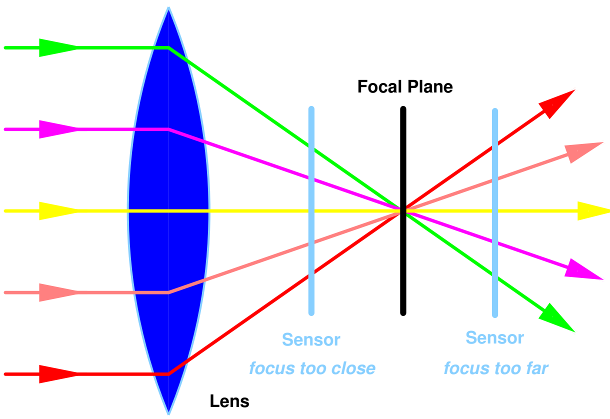


Figure 9. *Rays constructing an OOF PSF*

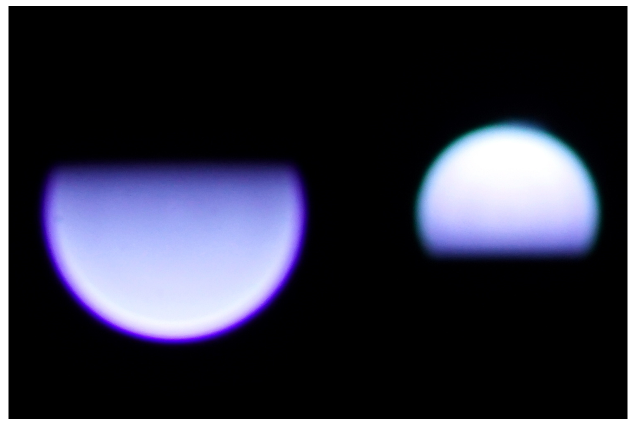


Figure 10. *EFCS clipping before and after the focal plane*

The unfortunate surprise in that EFCS can significantly damage the bokeh. Figure 8 reveals that, despite the bottom portion of the OOF PSF appearing as expected, the top of the OOF PSF gently fades to black. Why does EFCS clip OOF PSFs like that? The answer is closely related to the shading problem discussed in the previous section.

An OOF PSF is created by rays coming from the same point in the scene taking paths through the lens that do not converge on the sensor, as illustrated in Figure 9. As observed in the previous section, EFCS essentially tilts the slit so that rays at some angles cannot pass; this is not only true for rays coming from different objects, but also for rays coming through different portions of the lens from the same object. Because the rays that have the same angle swap sides (in our case, top vs. bottom) on opposite sides of the focal plane, EFCS clipping of OOF PSFs also flips which side of the OOF PSF is clipped. Figure 10 shows two actual measured OOF PSFs from a Samyang 85mm f/1.4 lens, one focused too close and the other too far away. Keep in mind that both clipping orientations can happen in the same image depending on the distances to the (multiple) point sources.

Perhaps the oddest thing about EFCS clipping of OOF PSF is that it does not happen with every lens. The ray angles depend on the precise design of the lens, and some lenses constrain rays to a range of angles that is not substantially clipped by the tilted slit. However, a lens that does have rays clipped will generally have a similar proportion of rays clipped despite modest changes in the focus, aperture setting, etc. Of course, using EFCS at slower shutter speeds adds unclipped exposure to the OOF PSFs, thus reducing the amount of clipping apparent.

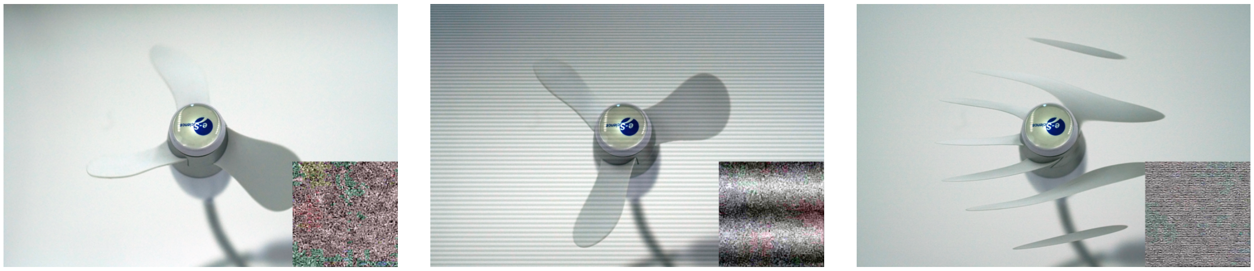
The full-frame mirrorless cameras announced in 2018 all have extra-wide lens mounts claiming that will allow larger rear elements to be closer to the sensor, making it easier to build wide-aperture lenses. Much of the motivation for fast lenses is to obtain better bokeh, but the larger rear elements will very likely cause severe clipping of OOF PSF using EFCS.

Slit Diffraction

Of course, there is no slit to cause diffraction using electronic shuttering, but slit widths between curtains can become surprisingly narrow, potentially limiting image resolution by diffraction; even the single curtain of EFCS could cause diffraction at its edge. Is this effect significant? Rather than attempting to measure small resolution changes, consider Fraunhofer diffraction caused by the moving slit:

$$d_f = \frac{2\lambda z}{W} \tag{1}$$

To be significant, the width of the central band, d_f, would need to be larger than the pixel size. Let λ be the wavelength of



Sony A7RII @ 1/8000s   Sony A7RII EFCS @ 1/8000s   Sony A7RII electronic @ 1/8000s

Figure 11. *Temporal artifacts involving both illumination change and subject motion*

green light (530nm), z be the approximately 7mm distance between the curtain and sensor, and W be a slit width of 1.2mm – values modeling a Sony A7RII. The result is $d_f = 6.18um$, whereas the pixel pitch in this 42MP full-frame cameras is $4.5um$, so the reduction in resolution would be negligible for color images using this Bayer-patterned sensor. Finer pixel pitches and somewhat larger z values (as found in Micro 4/3 cameras), or monochrome sensors, could make diffraction effects visible.

Temporal Artifacts

By far the best known artifacts introduced by shutters involve temporal artifacts caused by the skew in the time at which different pixel values are sampled. If the pixels are sampled in a regular, rectangular, sequential scan order, these are commonly known as rolling shutter artifacts.

There are two major types of temporal artifacts, *banding* (bright and dark lines) due to changes in scene illumination over time and *geometric distortion* due to motion of scene elements (or the camera). A scene with the potential for both of these types of motion artifacts was constructed by placing a spinning USB fan in lightbox using LEDs that can be dimmed by pulse-width modulation. This scene is shown in the three images of Figure 11. The inset image in the lower right corner of each image is a 2X enlarged sample from the image that has been contrast enhanced to make the artifacting more apparent.

Horizontal banding is clearly visible in the EFCS and electronic shutter images. The lighting here is provided by dimable LED lights for which the duty cycle is changed for a high-frequency on/off pattern. Cyclic changes in lighting are more often due to 50Hz or 60Hz flickering of many types of AC-powered apparently-continuous lighting. A single flash of light that lasts less than the shutter traversal time, such as firing of a strobe light, can also cause banding. The electronic shutter produces a dense line pattern because it is so slow to scan the frame. The other two images were captured at the same faster scan rate, so why does the EFCS image have line artifacts the mechanical shuttering does not? We believe the answer is again the tilted slit.

Geometric distortions depend on the rate of scene element motion compared to the speed at which the sensor is scanned. These artifacts are well understood. All types of focal-plane shutters suffer this defect[2], but most research is about electronic rolling shutters because they scan slower[3][4]. For simple linear motions, the distortion often looks like angular skewing, stretching, or compressing of the object; in video, the cyclic stretching causes "jello" distortion. More complex motions cause more complex spatio-temporal distortions – such as fragmentation of the fan blades in the electronic rolling shutter image. The faster curtain traversal kept the fan blades intact in the other images.

Conclusion

This paper has empirically measured a variety of shuttering artifacts, described their likely causes, and evaluated their overall impact. Shuttering artifacts are usually studied primarily in the context of electronic rolling shutters being used for video capture, but the current work is about understanding still-image shuttering artifacts. EFCS artifacts are particularly important, because EFCS has become the preferred shuttering implementation in mirrorless cameras. The main contribution here is the observation that, because EFCS electronic and mechanical "curtains" do not operate in the same plane, there is an asymmetry in which rays reach the sensor – causing a variety of unpleasant artifacts. At low shutter speeds, EFCS helps avoid inducing motion blur, but fast shutter speeds produce fewer artifacts with a mechanical focal plane shutter even if the two curtains are in a plane significantly in front of the focal plane. Purely electronic shuttering would be the most effective method if it scanned as fast as mechanical curtains move, and there is some hope for this: the Sony A9 electronic shutter is faster than some mechanical curtains.

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