The Sample-and-Hold Effect: Understanding Motion Blur and Motion Artifacts in Modern Displays

By: madVR Labs, LLC

1.0 Introduction

Our world thrives on visual experiences, and the displays that deliver these experiences have undergone massive transformations over the decades. From the bulky television sets of the past to the sleek screens of today, there has been a significant evolution in how we consume visual content. These contemporary screens, spanning LCD, OLED, SXRD, LCoS, and various laser projection technologies, represent the pinnacle of years of innovation. They offer astonishing resolution, a color spectrum broader and more vibrant than ever, and in some cases, astounding peak brightness needed for impactful HDR rendering.

But every tale of progress has its hurdles. The display evolution, for all its remarkable advancements, has intertwined with a series of challenges. The same pioneering technologies that bless us with mesmerizing visuals today have also introduced motion blur and sometimes judder. Judder refers to the jerky movement of objects on-screen, particularly noticeable during panning shots. These visual artifacts can detract from the viewing experience.

Such challenges arise predominantly because these modern display technologies use a method known as 'sample-and-hold' to display images, which keeps the same video frame on the screen until the next frame is displayed. This approach, while effective in many aspects, does not always gel well with our eyes' natural motion processing mechanism, and is contrary to how older display technologies operated.

The journey of display evolution is a fascinating one, marked by brilliant innovations, unexpected challenges, and solutions that often border on the ingenious. From the humble Cathode Ray Tube television sets that once graced living rooms worldwide, we now have wafer-thin OLED screens capable of displaying colors that CRTs could not even fathom.

In this paper, we'll journey through the evolution of display technologies, delving into the intricacies of how our eyes perceive motion and the challenges that modern displays have brought to the forefront when it comes to motion blur and judder.

2.0 The Evolution and Legacy of Film Projectors, CRT, and Plasma Displays

2.1 Film Projectors

Film projectors, long the stalwarts of cinemas, operate on a mechanical principle. Films are essentially a sequence of static images, and the projector displays these images one after the other at a rapid pace, typically 24 frames per second (fps). The rotating shutter of a projector blocks light intermittently, ensuring that there is a brief dark period between each frame. In order to avoid flickering, film projectors usually show each frame two or three times.

Motion Handling in Film Projectors: The intermittent darkness introduced by the rotating shutter represents a non-sample-and-hold approach, allowing our brain to merge these rapidly shown images into a seamless-looking moving picture. The resulting clean and sharp motion has a unique characteristic, often dubbed the "film look," which is distinct from the look of video content rendered on sample-and-hold type displays.

These legacy display technologies, although replaced in popularity, have set foundational standards in motion presentation, leading to current expectations and challenges as technology progressed.

2.2 Cathode Ray Tube (CRT)

The CRT was the quintessential television and computer display type for much of the 20th century. Comprising a large vacuum tube with an electron gun at one end and a phosphorescent screen at the other, CRTs created images by firing electrons at the screen. The rapid and continual scanning of electron beams, line-by-line, illuminated specific phosphors on the screen to create a full image.

Motion Handling in CRTs: CRTs inherently avoided motion blur because the phosphors would only briefly glow after being hit by the electron beam, fading quickly before the next frame began. This “fading” meant that at any given moment, only a small portion of the screen emitted light, which coincidentally worked well with the persistence of vision of our eyes. There was no sample-and-hold effect; thus, moving objects looked sharp and detailed.

CRTs had many downsides, though: The tube design required the CRT to be very deep, opposite of today's "flat" panel displays, extremely heavy, and severely limited the practical size of the display. Furthermore, the line-by-line scanning technique of the image resulted in noticeable flickering. In order to lessen the flickering, some CRT manufacturers switched to 100/120Hz, because at these higher refresh frequencies, flickering becomes much less visible.

2.3 Plasma Displays

Plasma displays, another major technology of yesteryears, created images using tiny gas cells positioned between two panels of glass. These cells, filled with a mixture of noble gasses, would become plasma when exposed to electrical currents, emitting ultraviolet light. This light then interacted with phosphors coated on the inside of the display to produce visible light.

Motion Handling in Plasmas: Similar to CRTs, plasma displays did not rely on a sample-and-hold method. The short-lived light bursts from the phosphors, coupled with the refresh strategy of plasmas, resulted in minimal motion blur. This made plasma displays popular among enthusiasts and professionals alike, especially for fast-moving content. However, Plasmas were not entirely free of motion artifacts, as the subfield driving method used in these displays could introduce its own set of motion artifacts. Plasmas were ultimately replaced by LCD displays, for various practical reasons, such as production costs, energy consumption and thickness. However, image quality was not one of the reasons.

3.0 Modern Display Technologies and Motion Challenges Due to Sample-and-Hold

As display technology has advanced from the era of CRTs and Plasma screens to modern digital displays, we have reaped numerous benefits, such as higher resolution, vibrant color gamuts, and significant improvements in both brightness and energy efficiency. However, these technological leaps have also introduced new challenges, most notably in the form of motion artifacts caused by sample-and-hold. The science behind how our eyes work and why this happens is covered in Section 4.

In the meantime, it is helpful to understand how various display technologies work, specifically considering their strengths and weaknesses in the context of 24-fps content. These technical details help explain why they are subject to artifacts from sample-and-hold.

3.1 OLED (Organic Light-Emitting Diode) Displays

OLED technology, characterized by its self-emissive nature, can turn individual pixels on and off. This results in incredible black levels and contrast ratios. Being a sample-and-hold technology, each frame in an OLED display is continuously displayed until the next frame replaces it.

3.2 LCD (Liquid Crystal Display)

LCDs operate by using a backlight to shine through liquid crystal cells, which act as shutters to create the image. Just like OLEDs, LCDs also use the sample-and-hold method, resulting in added motion blur and possible judder.

3.3 LCD and LCoS Projection

LCD and LCoS projectors have a light source which is then split into red, green and blue light spectrums, which are run through three separate LCD/LCoS panels (one for each primary color), and then merged for final output. Since the LCD/LCoS panels operate in a sample-and-hold manner, the same motion problems discussed previously are usually introduced.

3.5 DLP (Digital Light Processing) Projection

DLP projectors utilize tiny mirrors laid out in a matrix on a semiconductor chip, known as Digital Micromirror Device (DMD). Each mirror corresponds to a pixel and can tilt to reflect light towards or away from the projection surface. DLPs use Pulse Width Modulation (PWM) to create different intensities of different colors, which is to some extent similar to how Plasma displays worked.

Although DLP can largely avoid the sample-and-hold artifacts commonly seen in most other modern display technologies, it is not without its own quirks. For example, the use of temporal dithering to create images can introduce a different set of motion artifacts. Thus, while DLP's motion handling is generally better than sample-and-hold methods, it does not perfectly replicate the experience of film projection.

Advances in display technologies, while groundbreaking, have unintentionally highlighted the limitations of our visual system when presented with certain motion patterns. These challenges emphasize the importance of understanding human visual perception, its interaction with modern technologies, and the quest for solutions to deliver a cinematic experience devoid of distractions.

4.0 Human Vision and Motion Perception - The Impact of Sample-and-Hold

4.1 The Basics of How We See Motion

Our vision is a fascinating system, transforming captured light into the dynamic world around us. At its core is the ability to perceive motion. From the quick dart of a tennis ball to the graceful flight of a bird, our eyes and brain collaborate to track and interpret movement. This innate capability shapes our discussion on cinema and display technologies.

4.2 Persistence of Vision and Cinema's Illusion

Cinema's magic lies in its ability to create an illusion of motion from static images. Thanks to the phenomenon of "persistence of vision," our brains blend individual frames into fluid sequences. Traditional film projectors capitalized on this by flashing each frame just long enough for our brains to bridge the intervals, generating smooth motion.

4.3 Real-Life Motion vs. Display Motion

There is a world of difference between perceiving motion in reality and on a screen. Life offers us an unbroken stream of movement, while displays render motion using successive static images. While the objective remains consistent across evolving technologies, the methods of conveying this illusion have shifted, ushering in new challenges.

4.4 The Brain's Adaptation and Sample-and-Hold's Disruption

Our brains excel at filling in visual gaps, ensuring smooth and continuous perception. However, sample-and-hold display technology introduces a hitch in this process. By holding each frame static on the screen for the entire refresh period, sample-and-hold technology not only exaggerates existing motion artifacts but can also introduce new ones, such as added or exaggerated motion blur. This happens because as these images linger at a static position, our eyes, naturally designed to smoothly and continuously track movement, encounter a discrepancy.

Our eyes expect motion to be as smooth as it is in nature, but films shot at 24-fps do not look this way. This results in motion that appears somewhat jittery to us. This jitter makes the image look less clear than it should be, as evidenced by examining individual still frames from the 24-fps film.

The flicker introduced by film projectors and CRT displays helped our brain interpret the motion better, because the image was not held static at the same motion position for a prolonged period of time. Instead, the image just flashed shortly at the right motion position and then disappeared, which was easier for our visual system to process.

Therefore, with film projectors and CRT displays, we had smooth and relatively clear motion, but with some flickering. By comparison, with sample-and-hold displays, we avoid the flickering, but trade that advantage for jittery and blurred motion, potentially with some judder and double contours. The crux of the issue is that this can compromise the filmmakers' intended motion characteristics of the content.

Thus, the intrinsic challenge for modern displays becomes evident: Achieving flicker-free visuals at the expense of natural motion representation is a trade-off that has prompted the industry to aggressively seek techniques that better capture the essence of cinematic motion.

5.0 The Promise and Pitfalls of Modern Motion Handling Solutions

5.1 Why 24-fps Remains the Cinematic Standard

The film industry's enduring commitment to 24-fps is both a relic and a deliberate choice. Born out of early film's technical constraints, 24-fps emerged as the de facto standard by the 1930s. It was a rate that balanced film stock cost with perceived continuous motion, producing a sequence of images that appeared fluid to the human eye. But there is more to 24-fps than just economy and perception; there is an aesthetic that filmmakers and audiences have grown to love. The slight motion blur and the specific "feel" of 24-fps convey a sense of drama and weight. It has become synonymous with the "cinematic look" – a visual texture distinct from the hyper-real clarity of higher frame-rate video.

Yet, it's intriguing to ponder: what if the visionaries of cinema had standardized around a higher frame rate, such as 48-fps instead of 24-fps? Would today's filmmakers or audiences criticize 48-fps for being "overly fluid" or lacking the "cinematic essence"? While such a scenario remains speculative, it does prompt us to question whether our notion of the “cinematic look” is simply a product of familiarity, rather than an objective pinnacle of visual artistry.

5.2 Traditional Motion Smoothing and Its Shortcomings

With the evolution of digital displays, the quest to perfect motion representation began. Manufacturers developed various motion smoothing techniques to tackle the motion blur and judder challenges presented by sample-and-hold display technology. The two prominent solutions are Dark Frame Insertion (DFI) and motion interpolation.

DFI is a technique designed to emulate the visual characteristics of film projectors. In traditional projectors, a film frame is displayed for a fraction of a second before a rolling shutter momentarily blacks out the image, creating a flicker that reduces motion blur. DFI replicates this by intermittently inserting black or dark frames between the actual video frames. While this approach can successfully mitigate motion blur, it has drawbacks. The insertion of dark frames can reintroduce a degree of flicker, which may be distracting to some viewers. Additionally, the technique reduces the overall screen brightness, which is particularly detrimental when viewing High Dynamic Range (HDR) content that relies on peak brightness levels for effective contrast and impact.

Motion interpolation works by generating additional frames that are inserted between the original frames of the video, which creates the illusion of smoother motion. On paper, it sounds perfect – it allows the human eye to track the motion more faithfully, resulting in less judder and blur. But in practice, while motion interpolation can indeed minimize judder and blur, it often introduces problems of its own.

The most noted is the "soap opera effect." This term references the hyper-realistic look that interpolation often imparts, making cinematic content appear more like a daily soap opera shot on video. Moreover, fast-paced scenes or rapid camera movements can cause interpolation algorithms to falter, leading to visible artifacts such as tearing, blurring, ghosting, halos, and stuttering or unnatural motion. Furthermore, sometimes motion interpolation has the seemingly impossible task to understand a sequence of still images which may not always contain all the information needed to know which object on screen moves into which direction at which speed. Interpolation errors sometimes cannot be avoided in such difficult scenarios, resulting in motion artifacts.

5.3 The Role of Frame Rates

Frame rate is fundamental to how we perceive motion in video content. While 24-fps is the cinema standard, other frame rates have their specific uses and appearances. For instance, sports broadcasts, music concerts and some TV shows are shot at 50-fps or 60-fps, delivering a more "real-time" look that aligns with the immediacy of the content.

In recent years, there have been experiments with high frame rate (HFR) films. Peter Jackson's "The Hobbit" series, shot at 48-fps, and James Cameron's usage of both 24 and 48-fps in the making of "Avatar: Way of the Water" stand out as significant ventures into HFR filmmaking. While HFR does reduce motion blur, it also drastically changes the visual texture of the film. Audience reactions were mixed; some appreciated the clarity, while others felt it deviated too much from the traditional cinematic feel they are accustomed to. Furthermore, some viewers found the switching between 24-fps and 48-fps for different scenes in “Avatar: Way of the Water” to be distracting.

5.4 Sports and High-Frame Rate Benefits

When it comes to broadcasting fast-paced events like sports, higher frame rates can be a game-changer. Sports broadcasts often utilize 50-fps or 60-fps, as mentioned earlier, providing a clearer view of rapid movements, from a tennis ball's trajectory to the intricate footwork in a European football match. Given the real-time nature of sports, there is no "cinematic feel" to preserve, making clarity and fluidity top priorities.

Recent technological advancements have opened up the possibilities for increasing the frame rate to 120-fps for displays that can handle this higher frame rate, aiming to make fast-action sequences even smoother. Such a leap could make a significant difference in reducing blur and enhancing viewer engagement in sports or other high-speed content.

5.5 Towards a Holistic Solution

The quest for impeccable motion representation in modern displays has presented both progress and pitfalls. While techniques like DFI and motion interpolation offer solutions, they often come with trade-offs that can compromise the experience. But what if we could harness the benefits of higher frame rates and intelligent processing while minimizing the drawbacks?

Ultimately, the choice to employ techniques like DFI or motion interpolation rests with individual viewers, each of whom must weigh the benefits against potential drawbacks.

Some may opt for the most lifelike, smooth visuals and employ a strong level of motion interpolation, while others might gravitate towards a more cinematic experience, perhaps by using DFI, or a very subtle amount of motion interpolation to stay closer to the director's intent. In the end, the freedom to customize one's viewing experience lies with each user, provided such options are available for their choosing.

From a technological standpoint, the path forward involves refining existing techniques and potentially developing entirely new solutions. Could DFI be fine-tuned to minimize flicker and brightness loss? Might advancements in AI-based algorithms allow for higher-quality motion interpolation with fewer artifacts and finer control over the amount of soap opera effect? Or perhaps a hybrid approach that combines high-quality AI-based motion interpolation algorithms with improved DFI could serve as a viable alternative? It is also conceivable that new methods could emerge, designed to mitigate issues like judder and sample-and-hold blur without sacrificing the cherished cinematic look.

About madVR Labs, LLC.

madVR Labs is a leading provider of advanced video processing algorithms designed to enhance the visual experience in high-end home theaters and media rooms. The company's flagship product, the madVR Envy Extreme, is distinguished for its state-of-the-art features including proprietary frame-by-frame dynamic tone mapping, AI-based upscaling, instant aspect ratio detection, and non-linear stretch, all within a user-friendly interface. Committed to continual innovation, madVR Labs is investing heavily in the development of next-generation solutions like MotionAI, which leverages artificial intelligence for improved motion interpolation, as well as for developing new AI-driven algorithms in other areas of video processing.