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PHYSICS-BASED SIMULATION OF REALISTIC LIGHTING AND ILLUMINATION FOR NEXT GENERATION GROUND VEHICLE IMAGE GENERATORS

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ABSTRACT

Over the past several years, the rate of advancements in modern computer hardware and graphics computing capabilities has increased exponentially and provided unprecedented opportunities within the Modeling and Simulation community to increase the visual fidelity and quality in new Image Generators (IGs). As a result, IG vendors are continuously reevaluating the best way to make use of these new performance improvements. Some vendors have chosen to increase the resolution of the environment by displaying higher resolution imagery from disk while other vendors have chosen to increase the number of polygons that are capable of being presented in the scene while maintaining 60Hz. While all of these approaches use the latest hardware technology to improve the quality of the simulated environment in the IG, the authors of this paper have chosen to focus on a different approach; to improve the ***accuracy*** *and* ***realism*** *of the simulated environment. To accomplish this, the authors have developed capabilities that exploit the modern advances in hardware and graphics processing to mimic the human vision system and improve each pixel with enhanced atmospheric and illumination calculations improving the accuracy and realism of these pixels on the display's surface.*

INTRODUCTION

Modern day computer hardware and graphics computing capabilities continue to increase at an exponential rate. As the hardware advances, Image Generator (IG) vendors are continuously reevaluating the best way to make use of these new performance improvements. Some vendors may choose to use hardware improvements to increase the number of polygons capable of being presented in the scene while maintaining 60Hz. Other vendors may choose to page more high resolution imagery from disk, and yet others, may use the hardware improvements to generate database content at run-time. While all of these approaches to improving simulation fidelity and realism have their unique benefits (and drawbacks) the authors of this paper have chosen to focus on a different approach to improve realism and fidelity. The authors have chosen to focus on exploiting the modern advances in hardware and graphics processing to mimic the human system and improve the *quality* of each pixel with enhanced atmospheric and illumination calculations in order to improve the realism of these pixels and their final red, green, and blue luminance levels on the display's surface.

The ultimate goal of the author's efforts is to improve the realism of visual and sensor simulations by trying to imitate the effects that our human visual system perceives in the real-world environment and display them in a simulated environment. As such, the focus of this paper describes new capabilities that can be integrated into various vehicle driving simulations to immediately improve fidelity and realism. The goal of this paper is to present the improvements in accuracy and realism that can be obtained in visual and sensor simulations by imitating the effects our human visual system 'sees' in the real-world and displaying them in a simulated environment. Our human vision system is capable of adapting to vastly different luminance levels (i.e., light levels) that can extend to a range of up to 14 orders of magnitude; yet, simulation display systems are only capable of producing an illumination range of approximately 3 orders of magnitude. Therefore, in order to mimic how our visual system perceives the vast ranges of illumination levels in a simulation, physics-based rendering techniques must be employed to emulate certain effects experienced in our human visual system (i.e., glare and adaption) while accounting for the limitations of the display. This involves the physics-based modeling of light propagation in the ambient environment in High Dynamic Range (HDR) while also modeling the variations in human perception in order to view the results on Low Dynamic Range (LDR) displays. The prediction of visibility and appearance of scene features using our approach provides significant improvements in realism and enhances the overall quality of ground vehicle simulations. The resulting realism can significantly improve training when high contrast scene content is present and more accurately represent conditions experienced in the real-world. This paper will show the results and improvements that can be obtained by mimicking various aspects of the human vision system in next generation IGs for ground simulations.

In the real world, the human visual system is capable of adapting to vastly different luminance levels (i.e., light levels) that can extend to a range of up to 14 orders of magnitude [10]. For instance, the sunlight on a clear summer day can be as much as 10 million times more intense than the illumination from the moon later that night [6]. Figure 1 shows the large range of luminances in the environment and some associated visual parameters as an example. Therefore, in order to mimic how our visual system perceives the vast ranges of illumination levels in a simulation, it seems logical that we would replicate the exact same luminance levels in the simulation display system. However, while physics-based rendering methods enable the accurate simulation and distribution of light energy rendered in day and night scenes, most simulation display systems are only capable of producing an illumination range of approximately 3 orders of magnitude (compared to the 14 orders of magnitude perceived by the human vision system). Therefore, accurate physics-based rendering does not automatically guarantee the realistic visual appearance of a displayed scene. Additional rendering techniques are required to mimic certain effects experienced in our human visual system (i.e., glare and adaption) while accounting for the limitations of the display.

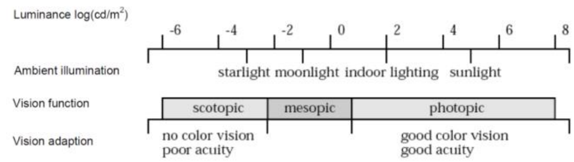

Figure 1: Range of Luminances and Visual Parameters. After Ferwerda, et. al., [6]

This paper discusses how the authors have improved the realism of visual simulation by emulating the adaptation of the human visual system to varying driving and vehicle conditions. This involves the physics-based modeling of light propagation in the ambient environment in High Dynamic Range (HDR) while also modeling the variations in human perception in order to view the results on Low Dynamic Range (LDR) displays. Figure 2 below illustrates the night driving realism which can enhance the overall quality of training through the approach proposed here.

Figure 2: Night driving. The proposed approach to physics-based modeling of light will improve the realism and therefore training results of ground vehicle driving simulations under a wide variety of environments and conditions.

BACKGROUND AND RELATED WORKS

Understanding how the human visual system works and the mechanisms involved in the perception and adaptation to different illumination levels experienced in the real-world lends support to the innovations presented here. The adaption of the human vision system is achieved through a combination of mechanical, photochemical, and neural processes in the visual system. The pupil, the rod and cone systems, and changes in neural processing play a major role in the adaptation mechanism. However, not all intensity levels are perceived equally well, and adaptation does not happen instantaneously, especially under the wide range of environments and conditions faced by ground vehicle assets.

It is convenient to think of the human vision system as a complex ‘biological sensor’ comprised of rods and cones that adapts to ambient illumination with the three vision functions:

- scotopic vision, that is active at a luminance range of approximately 10−6 to 10-2 cd/m2
- mesopic vision, that is active at a range of ~10-2 to 1 cd/m2, and
- photopic vision, that is active at a range of ~1 to 106 cd/m2 [1].

Figure 3 (below) illustrates how the spectral sensor response curves of rods and cones change for the scotopic, mesopic, and photopic vision functions. Knowing and simulating the state of this biological sensor is a key component in determining what an observer should be able to distinguish in the virtual scene under different simulated lighting conditions. Significant advantages in ground vehicle training can be achieved through emulating the scotopic, mesopic, and photopic vision functions, the differences in perception at different luminance levels, including the dynamic characteristics.

One of the most important aspects in modern vehicle and driving simulations is the ability to accurately display realistic synthetic environments and scene content while maintaining real-time rendering performance. For example, imagine being able to offer highly realistic weather or lighting conditions for different terrains, including non-road terrains, faced by our ground vehicles in different areas of the world. Accurate modeling of natural illumination and how the atmosphere modulates and contributes to this has become increasingly possible. Some of the reasons why this is advantages are as follows:

- Realistic radiance values tend to produce expected, reproducible results.
- When ‘tuning’ a scene that starts with real-world values, it is easy to determine how much each "tweak" deviates from reality, which in turn helps determine the resulting numerical accuracy of the system.
- Less visual tricks are required to produce desired final results that appear and behave like the natural environment.

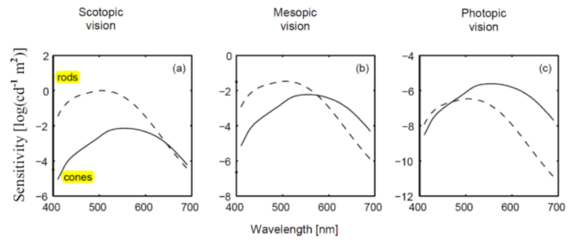

Figure 3: Spectral Response Curves of Rods and Cones for a) Scotopic, b) Mesopic, and c) Photopic Vision [6]. Combining the 3 different response curves in simulations to improve the realism of the scene as it presents a more accurate representation of how the human eye is viewing the scene.

Moreover, the accurate and realistic display of synthetic environments are highly dependent on the correct depiction of illumination levels and atmospherics of the virtual scene. One of the growing methods for replicating the dynamic lighting conditions of the real-world in visual simulations and gaming platforms is to use High Dynamic Range Rendering (HDRR).

Most of today’s digital images are stored with 24-bits per pixel, which allows for values from 0-255 for each of the red, green, and blue channels. However, in our natural (real-world) environment, the light intensities and brightness levels greatly exceed what can be accurately represented with 8-bits per-channel digital images. While it is convenient to use the integer values 0-255 to represent RGB pixel values, there are not enough gradations or steps to accurately represent the wide range of real-world light levels. Therefore, to more accurately replicate the natural driving environment and the highly variable conditions faced by our ground vehicle troops and the way our Human Vision System (HVS) interprets the scene, color and luminance values need to be represented as floating point values that cover a much larger range (ie., the ratio between the highest and lowest values of luminance in a scene or image and is usually expressed in orders of magnitude) [8]. HDRR provides more realistic and convincing visual effects since the pixel values more accurately reflect the light levels of real-world vehicle operation.

Although HDR imagery and rendering techniques are relatively new, the use of HDRR has been rapidly expanding in the gaming and simulation industries largely as a result of the equally rapid advancements in GPU capabilities. This has prompted significant research in recent years on different real-time HDRR techniques. For instance, Petit & Bremond [12, 13] proposed a noteworthy method to compute in real-time a HDR illumination in virtual environments based on physical lighting models. Their method allowed for the re-use of existing virtual environments as input to compute the HDR images in photometric units rendered with a tonemapping operator on a Low Dynamic Range (LDR) display. Their approach, which conducted the HDR computation and tonemapping operations in *OpenSceneGraph* using pixel shaders, provided enhanced perceptual realism of the scene at a low cost to performance and operation in the rendering pipeline. They demonstrated the results of their HDR pipeline with an interactive driving providing enhanced (realistic) lighting.

Similarly, Delacour [4] developed a simulation framework with a display and environment designed to mimic the visual perception a human would have of the scene in real life. His goal was to build a simulator based entirely on physics and the physiological perception of light using HDRR techniques combined with the interactions of the physical simulation interfaces. In addition to providing accurate displays of the synthetic environment in the simulation framework proposed by Delacour [4], his approach also provided designers the ability to accurately simulate the lighting within the simulation platform to improve the decisions on Human Machine Interface design.

HDRR provides the ability to represent each pixel with a larger contrast ratio and dynamic range to more accurately represent real-world conditions. The intensity of the pixels can even have a dynamic range greater than the range available on the display. In the cases where the values of the HDR exceed the values of the display, a transformation is usually applied in the rendering pipeline to convert the HDR values to LDR values for the display [7]. This transformation is commonly referred to as tonemapping and is done using tonemapping operators (TMO) [16].

The importance of tonemapping operations in HDRR is widely understood and many research studies have already proposed algorithms to perform efficient TMOs achieving real-time performance [3]. In one example, Krawczyk, et. al., [7] presented an efficient way to maintain the most significant perceptual effects in HDRR (i.e., glare, bloom, visual acuity, night vision, etc.,) with real-time local contrast compression (tonemapping) for LDR displays. The result was a unified model including all of those effects into a common framework that ran on common hardware and could be added into any real-time rendering system to enhance the realism and believability of the displayed environment.

OVERVIEW

The authors' solution divides simulating the human vision system into two separable components:

- The scene is rendered using true radiance values as opposed to the unitless 0 to 1 values typically used for out-the-window scenes.
- To support the human vision system, the authors then render the scene using radiance values in the photopic red, green, and blue wavebands. The rendered scene is captured as floating point values and processed in a way that simulates the human visual system's response to these radiance values. The radiance value to final output pixel values incorporates graphics processing similar to that performed by a traditional sensor post-processor.

It is worth noting that much of the processing involved in simulating the human vision system is similar to that used to simulate Night Vision Goggles (NVGs) and Forward Looking InfraRed (FLIR) sensors.

Two software libraries, called SERE (Synthetic Environmental Radiometric Engine) and ICSM (Inter-service Common Sensor Model), have been developed to facilitate these two tasks. These libraries can be dropped into virtually any scene graph to improve visual and sensor representations. SERE provides direct rendering of the sky, sun, stars, etc. in addition to shader code used by the scene graph to render true radiance values. In the Figure 4 below, SERE's domain is represented by the arrows in the scene and those that point to the observer. SERE supports rending in the wave lengths from photopic blue through long-wave infrared. ICSM facilitates the capturing of the scene into a floating-point Frame Buffer Object (FBO). ICSM also provides the math model and graphics processing needed to emulate the human vision system, NVG sensors, and FLIR sensors. In the figure below, this domain is referred to as the observer (detector) transformations on the right.

While SERE and ICSM are crucial to the work presented in the paper, the focus of this paper is on leveraging these libraries in a training environment as opposed to the implementation details of these libraries. SERE and ICSM can be integrated into various vehicle driving simulation tools to immediately improve the fidelity of the simulations. The CIGI interface provided also allows for host control and can synchronously render across multiple computers in order to generate a contiguous image that provides a wide field of view.

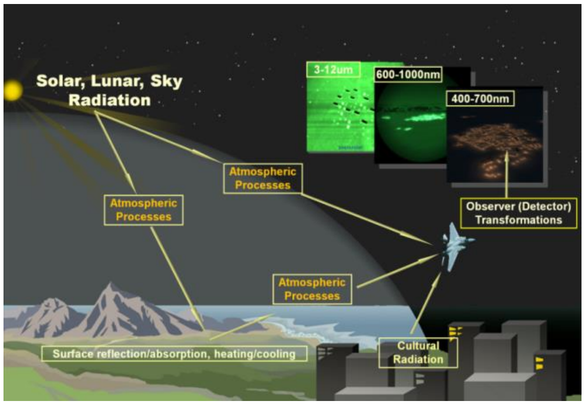

Figure 4: Components of Radiometric Simulations. By rendering true radiance values using SERE and capturing scenes in floating-point values using ICSM, the authors have been able to create more realistic simulations of driving environments through re-creating how the human visual system actually perceives the scene.

REAL-WORLD ILLUMINATION LEVELS

In order to model the lighting environment using values that are representative of the real-world, let us first discuss the levels requiring consideration. Full daylight is roughly 10 orders of magnitude greater than clear starlight conditions. Dividing the environments into two operational conditions, night and day respectively, large spans of intensities still remain. Excluding the extremes, overcast conditions in starlight and manmade lighting, the illumination spans roughly four orders of magnitude. With typical manmade lighting it can be around 7 orders or greater. During daytime on a clear day, sunrise and sunset to high noon, we encounter roughly 3 orders of magnitude in illumination. Table 1 illustrates typical illumination levels, including those commonly associated with vehicle operation.

Table 1. Typical Illuminance Levels at the Ground. The following illumination levels, including those for standard places of vehicle operation, can be precisely re-created with the approach presented here.

Condition	**Illumination Level (*lux*)**	**Illumination Level (*fc*)**
Clear night sky (no Moon)	0.00005 - 0.002	0.000005 - 0.0002
Clear urban sky with light pollution	0.015	0.0014
Beginning of astronomical twilight	0.1	0.009
Overcast urban sky with light pollution	0.15	0.015
Full Moon	0.2 (typical) to 1 maximum	0.019 (typical) to 0.093 max
Urban road with artificial illumination	2	0.19
Open parking lot	11 - 22	1 - 2
Car dealership lot	200	19
Sun(rise/set) on a clear day (ambient illumination).	400	40
In shadow at noon, clear sky	~5000 - 10000	500 - 1000
Full sunlight	100,000	~10,000

DISPLAY LIMITATIONS

Display systems, whether direct view as in flat panel displays or indirect view as in projected displays, are greatly limited in the dynamic range of the intensities they can produce. The next few paragraphs are mainly intended as background information and to highlight the problems created by the limitations versus a full analysis of the challenges faced by display systems.

Manufacturers of projection systems commonly tout large dynamic range capabilities for their products. These ranges are measured in strictly controlled scenarios and typically do not stand up to the challenges of actual use. It is also common for display manufacturers to quote numbers representing their display systems dynamic contrast. Dynamic contrast is the ratio of the brightest instance (frame) as compared to the darkest instance (frame) usually using the full field of view. A contrast measurement that better reflects the real world use cases is referred to as static contrast.

Static contrast is the measurement of the brightest part of a single frame as compared to the darkest part of the same frame. Some numbers for dynamic contrast from leading manufacturers span 6 orders of magnitude. However, these same projectors are barely capable of having static contrast ranges of 4 orders of magnitude on a flat surface and 2 orders of magnitude in cases where screen cross illumination is heavy.

In practice, 4 fL (foot-Lamberts) is used as a typical calibration luminance in many simulation installations. Many factors push users to select this value. One is that this value has been found to be a good setting that allows for both day and nighttime scenarios with little or no projector setting changes. Another factor is to prolong the life of the bulb in the projectors (for those that have bulbs). To put this 4 fL luminance value into perspective, below is an equation for asphalt viewed at night under artificial lighting conditions in a car dealership parking lot:

$$L_v = E_v \times R$$

Where:

L_v is the luminance, in foot-lamberts [fL]
E_v is the illuminance, in foot-candels [fc]
R is the reflectivity, expressed as a fractional number
3.8 fL = 19 fc * 0.2 (20%)
* 20% is a typical reflectance value of older asphalt.

The limited dynamic range of display systems may seem problematic, but once the user has viewed the simulation for some time, the human visual system tends to adapt and accept this as a daytime image. Of course, there are systems currently deployed or coming online which are calibrated to higher intensities for daytime use and can be adjusted for nighttime vehicle operation training. However, these increases do not represent orders of magnitude improvements, but simply modest incremental improvements. One reason for this is that increasing the top end brightness commonly increases the bottom end (black level) as well. In bright scenarios, this may not be as noticeable, but for nighttime scenes the black levels can become visible and distracting.

SIMULATING THE HUMAN VISION SYSTEM

The experimental IG utilized for this effort uses ICSM to simulate the human vision system. In many ways, the ICSM software plays a role similar to that of traditional hardware sensor post-processor systems, except that it is largely implemented on the GPU. The input interface from the experimental IG to ICSM is largely accomplished by “handing off” at-aperture radiance frames. In this interfacing approach, the implementation details associated with scene generation are largely hidden from ICSM as presented in Figure 5.

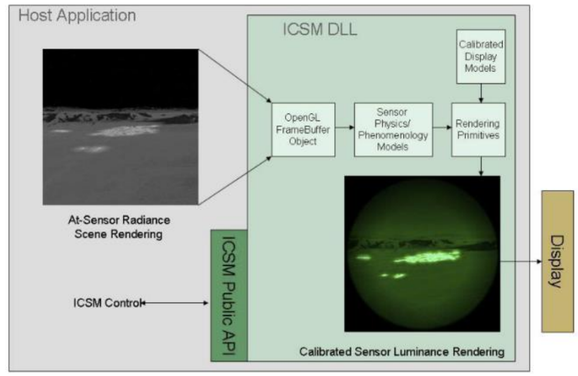

Figure 5: Sensor as Post-Processor. Example of some common sensor processes that are used create to high-fidelity scenes.

ICSM provides many features as part of its simulation of the Human Vision System. A few of the more relevant feature are discussed below.

Gain

HDRR commonly uses tonemapping for converting from floating-point pixel values to 24-bit integer values that are sent to the display system. ICSM performs this task by computing the average scene radiance and approximates what the observer should see in their simulated adaption state on the target display system. It should be pointed out that if the display system is capable of generating real-world luminance levels present in a given scene, ICSM is able to generate pixel values resulting in accurate luminance levels on the display’s surface. Most display systems are not capable of displaying clear starlight or daytime illumination levels, so some amount of tonemapping is generally required.

Night Adapted Vision

The human vision system functions significantly different at night then it does during the day, a very important factor in proper roadway and terrain navigation for ground vehicles. Acuity and color perception are significantly different at night than they are during the day. If the display system is incapable of reproducing all of the required values of a nighttime scene or the observer is not able to adapt to nighttime vision, due to the training room's ambient lighting conditions, ICSM can facilitate simulating reduced acuity and a shift in color perception.

Glare

Full scene glare or bloom is a technique video games have made popular in recent years. In some implementations, it produces surreal looking image that are less stark than when not employing this technique. Although full scene bloom can produce impressive looking results, it can also produce unrealistic images when overdone. The premise behind this technique is valid. When our eyes view something that is too bright for our current adaption state, light from this source will scatter within our eyeball and the light will appear to bloom around this object. Our eye is an imperfect imaging sensor. Our lens has imperfections in it and the liquid inside and outside our eye is not perfectly clear. The older we get, the more these imperfections become noticeable.

The authors contend that glare is an important part of some training exercises, such as driving in high sunshine conditions. The sun can skew a driver's perception on straight, easy to navigate roadways. Not recognizing the glare from sun in training simulations, and the fact that ground vehicles are also off-terrain in hard to navigate conditions, leads to simulations which do not produce accurate training and realistic results. Without adding a glare effect to ground vehicle simulations, the trainee's perception of navigating vehicles under these conditions will be overly simplified. This is because the display system cannot represent the true intensity of sun. Therefore, current simulators commonly provide negative training in these situations. The left half of Figure 6 contains an image of the glare effect that is part of ICSM. In this image, the bright sun is reflecting off a roadway, partially obscuring the driver's vision. The amount of bloom that is applied must be scaled according to the capabilities of the display system.

Another common occurrence of glare can be light points, particularly bright light points at night. A good example of this is the bloom we see around approaching car headlights on a dark night. Ideally, a display system would be able to generate luminance values that matched that of light points in the real world. Unfortunately, such display systems do not exist for visual simulations. However, knowledge of the true radiant intensity of a light point and the current adaption state of the observer can enable software to place an appropriate amount of bloom around light points, much like when simulating an NVG sensor. This effect must also be tuned to the display system's capabilities.

Simulating Analog Output

Light levels in the real-world are analog, whereas display systems are commonly digital devices that have a limited number of intensity values they can reproduce. The intensity differences between these discrete values can sometimes be seen when simulating subtle gradations, such as the road near the horizon line.

Figure 6: Glare Effect. Glare from sunshine can impact a driver's vision and therefore their ability to navigate the variety of driving terrains they may face.

When you closely examine a photographic image containing a smooth gradation, you commonly see a small amount of noise in the image. Without this noise, the image would likely contain color banding. In the authors' solution, the entire scene is rendered using floating-point radiance values in a buffer and then converted into quantized discrete integer values. By adding a very small amount of noise when converting from floating-point values to integer values, banding artifacts are avoided.

The authors have also developed a method for adding a dynamic noise pattern each frame, which not only prevents the observer from detecting the noise pattern, but also enables the observer to perceive intensity values that the display system is unable to produce. As an example, let's say the desired pixel value is (127.5, 127.5, 127.5). Let's assume the display hardware can only reproduce the pixel values (127, 127, 127) and (128, 128, 128). By showing the observer the pixel value (127, 127, 127) on all even frames and (128, 128, 128) on all odd frames, the observer would perceive the intended value of (127.5, 127.5, 127.5). By extrapolating this idea, the authors have achieved perceived results significantly closer to the original floating point values in the rendered scene and have eliminated banding artifacts.

INTEGRATION INTO GROUND VEHICLE EXPERIMENTAL IMAGE GENERATOR

The experimental IG used for this effort is a software application that was developed by Renaissance Sciences Corporation (RSC) to provide simulation of the human vision system, light intensifiers, and thermal imagers. The goal was to create an application performing complex radiometric computations and sophisticated viewer transforms while maintaining real-time frame rates (60 Hz) at high resolutions

(2560x1600). There is no question SERE and ICSM consume CPU and GPU resources. However, the authors' work has shown modern day off-the-shelf gamer class computer hardware is fast enough to render required database content, perform this processing, and still meet real-time simulation requirements.

This IG has been implemented to enable the underlying scene graph to be changed relatively easily, while still providing many of the same features, including its CIGI interface and synchronization capabilities. The underlying rendering engine is currently OpenSceneGraph (OSG), although the authors have also successfully leveraged other commercial IGs is this role.

SERE has been integrated predominantly in two ways. First, an OSG specific SERE adapter has been created. This adapter facilitates the construction, loading, and updating of SERE shaders that can be attached to any OSG node in the scene graph. Second, SERE is told when it should directly render the sky dome, sun, and stars at the beginning of each frame.

Figure 7 illustrates how ICSM's processing is integrated into the experimental IG's frame loop. The time axis starts on the left. The light gray background indicates that the IG's code is being executed; the dark green background indicates that ICSM's code is being executed; and a red line around a buffer indicates that buffer is the active OpenGL render target. Indication of which buffer is active and the contents of the buffer are based on the state of the IG at the end of each block in the diagram. It is important to note that when the IG is rendering the scene, the ICSM buffer is active. Similarly, when ICSM is rendering, the frame buffer is the active buffer.

In order to minimize latency, the IG uses a single thread for all app, cull, and draw processing. As stated above, the IG performs accurate floating-point radiance based rendering and simulates the human vision system. All of the processing required to construct, render, post-process, and synchronize a single frame consistently stays below 11 ms.

CONCLUSION AND FUTURE WORK

The goal of this effort was to create an experimental IG capable of incorporating aspects of the human vision system to increase the realism and accuracy of the simulated environment while still maintaining the commonly accepted requirements for frame rate and resolution. To achieve this, the authors emulated the adaption of the human visual system in the experimental IG to accurately render the scene using floating-point radiance values and post-processing techniques to compensate for the limited dynamic range of typical display systems. This involved the physics-based modeling of light propagation in the simulated scene in High Dynamic Range (HDR) while also modeling the variations in human perception in order to view the results on Low Dynamic Range (LDR) displays. The results of this ongoing effort have shown significant improvements in the visual fidelity and perceptual accuracy (i.e., realism) of the rendered scene.

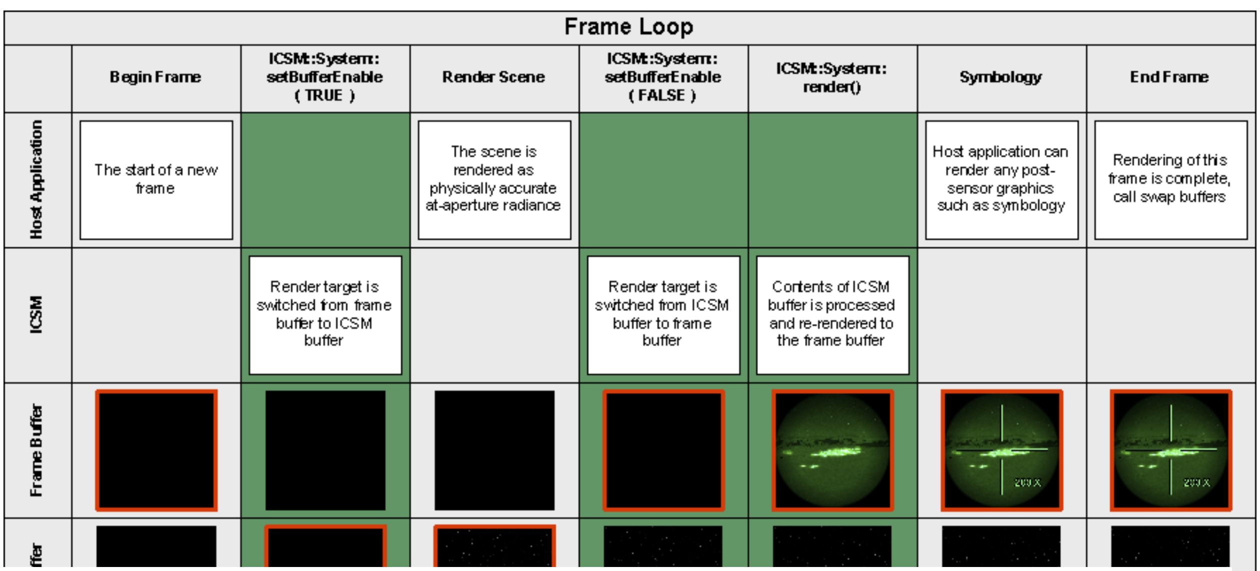

Figure 7: Example of ICSM processes and how it can be integrated into the simulation processing loop rendering more accurate scenes.

The development of the software discussed in this paper has been deployed as a series of Commercial Off The Shelf (COTS) SDKs and plug-in applications for existing IGs called SimHDR (for visual 'out the window'), SimHDR-EO (for NVG stimulation), and SimHDR-IR (for thermal display). Furthermore, the authors are hopeful that this paper will help push the state of the art for realism in next generation ground vehicle simulation Image Generators.

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