A Hybrid System for Real-Time Rendering of Depth of Field Effect in Games

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Abstract: Real-time depth of field in game cinematics tends to approximate the semi-transparent silhouettes of out-of-focus objects through post-processing techniques. We leverage ray tracing hardware acceleration and spatio-temporal reconstruction to improve the realism of such semi-transparent regions through hybrid rendering, while maintaining interactive frame rates for immersive gaming. This paper extends our previous work with a complete presentation of our technique and details on its design, implementation, and future work.

1 INTRODUCTION

We present the design and evaluation of a novel real-time hybrid rendering approach for the Depth of Field (DoF) effect which incorporates post-process based DoF with temporally and spatially reconstructed ray trace based DoF. By adaptively combining the output of different passes, we achieve more accurate semi-transparencies of foreground geometry to reveal background objects. We believe that our hybrid DoF technique is the first to integrate a ray-traced output with a traditional post-processing pipeline.

Building on our previous work (Tan et al., 2020a), the key contributions of this paper are as follows.

• Design and implementation of a real-time hybrid rendering pipeline for DoF.
• Visual quality evaluation of the hybrid method, specifically, the accuracy of semi-transparencies.
• Performance evaluation and trade-offs in the use of ray tracing for DoF.

1.1 Background Information

Current DoF implementations in game engines typically use the thin lens model (Potmesil and Chakravarty, 1982) to approximate the behaviour of cameras. The zone of focus is the part of the scene where the objects look sharp. The Circle of Confusion (CoC) (Demers, 2004) of points in the zone of focus are smaller than a cell on the sensor, yielding a single pixel in the image, whereas points outside the zone of focus appear as a spot on the image based on their CoC. For such points which lie on the same object, an overall blur of the object is produced.

Bokeh shapes, which are bright spots created by a beam of unfocused light hitting the camera sensor, appear in areas out of the zone of focus. They usually take the shape of the camera’s aperture and can have circular or polygonal frames depending on the number of blades in the camera shutter.

Blurred foreground objects also have a slightly transparent silhouette through which background colour can be observed. These semi-transparent edges cannot be properly rendered in games with post-processing as the image does not store any information behind a foreground object (Kraus and Strengert, 2007). However, such approaches are widely used in real-time rendering as images produced by rasterization are in sharp focus (McGraw, 2015). According to Jimenez (2014), many techniques can only perform an approximation of the background colour locally using neighbouring pixels like in Abadie (2018) or grow blur out of the silhouette of foreground objects onto background colour, reusing foreground information to avoid reconstructing the missing background. However, shifting the blur outwards from foreground objects produces inaccuracies with regards to their actual geometries, especially when the amount of extended area is comparable to the size of the objects themselves. Objects with more elaborate shapes also
tions. Barré-Brisebois et al. (2019) is also one such
mination and ray tracing for reflections and refrac-
tions. Nonetheless, achieving interactive frame rates
with ray tracing is difficult due to the high computa-
tional costs of calculating ray-geometry intersections
and multiple shading for each pixel, even with the lat-
est GPUs developed for ray tracing. Hence, hybrid
rendering, which aims to combine existing rasteriza-
tion techniques with ray tracing, is being researched.

2 RELATED WORK

2.1 Hybrid Rendering

Examples of hybrid rendering on related effects in-
cude Macedo et al. (2018) and Marrs et al. (2018)
which invoke ray tracing for reflections and anti-
aliasing respectively only on pixels where rasteriza-
tion techniques are unable to achieve realistic or
desirable results. Beck et al. (1981), Hertel et al.
(2009) and Lauterbach and Manocha (2009) employ
the same strategy to produce accurate shadows.

The concept of hybrid rendering can also be ex-
tended to general rendering pipelines. For example,
Cabeleira (2010) uses rasterization for diffuse illu-
mination and ray tracing for reflections and refrac-
tions. Barré-Brisebois et al. (2019) is also one such
pipeline that has replaced effects like screen-space re-
fections with their ray trace counterparts to achieve
better image quality. Another commonly-used ap-
proach is Chen and Liu (2007), the substitution of
primary ray generation with rasterization in recursive
ray tracing by Whitted (1979). Andrade et al. (2014)
improves upon this technique by observing a render
time limit through the prioritization of only the most
important scene objects for ray tracing.

2.2 DoF

Many DoF rendering techniques have been devised
over the years. Potmesil and Chakravarty (1982)
first introduced the concept of CoC for a point based
on a thin lens model which simulates the effects of
the lens and aperture of a physical camera. It em-
loyes a post-processing technique that converts sam-
ples points into their CoCs. The intensity distribu-
tions of CoCs overlapping with each pixel are then
accumulated to produce the final colour for the pixel.
Haeberli and Akeley (1990) integrates images ren-
dered from different sample points across the aper-
ture of the lens with an accumulation buffer. On the
other hand, Cook et al. (1984) traces multiple rays
from these different sample points on the lens into the
scene using a technique now commonly known as dis-
tributed ray tracing, for which improvements in ray
budget have been made in Hou et al. (2010) and Lei
and Hughes (2013).

For rendering with real-time performance con-
straints, spatial reconstruction and temporal accumu-
lation approaches have also been developed. For in-
stance, Dayal et al. (2005) introduces adaptive spatio-
temporal sampling, choosing to sample more based
on colour variance in the rendered image with selec-
tive rendering by Chalmers et al. (2006) and favouring
newer samples for temporal accumulation in dynamic
scenes. Schied et al. (2017) also uses temporal ac-
cumulation to raise the effective sample count on top
of image reconstruction guided by variance estima-
tion. Such techniques have been applied for DoF such
as in Hach et al. (2015), Leimkuhler et al. (2018),
Weier et al. (2018), Yan et al. (2016) and Zhang et
al. (2019). More advanced reconstruction techniques
for DoF have also been introduced, such as Belcour et
al. (2013), Lehtinen et al. (2011), Mehta et al. (2014)
and Vaidyanathan et al. (2015) which sample light fields
as well as Shirley et al. (2011) which selectively blurs
pixels of low frequency content in stochastic sam-
pling. A more adaptive temporal accumulation ap-
proach from Schied et al. (2018) which is responsive
to changes in sample attributes such as position and
normal has also been proposed to mitigate ghosting
and lag in classic temporal accumulation approaches.

Micropolygon-based techniques have also proven
to be capable of DoF like in Fatahalian et al. (2009)
and Sattlecker and Steinberger (2015). Catmull
(1984) solves for per-pixel visibility by performing
depth sorting on overlapping polygons for each pixel.
Following this, approaches based on multi-layer im-
ages like Franke et al. (2018), Kraus and Strengert
(2007), Lee et al. (2008), Lee et al. (2009) and Sel-
grad et al. (2015) have also been introduced where the
contributions from each layer are accumulated to pro-
duce the final image. Such layered approaches are
computationally expensive although they can gen-
erate relatively accurate results in terms of semi-
transparencies, Bukowski et al. (2013), Jimenez
(2014), Valient (2014) and state-of-the-art Unreal En-
gine approach Abadie (2018) divide the scene into
the background and foreground, and runs a gathering fil-
ter separately for each. We adopt such a technique,
which performs better in terms of rendering time even
in comparison to Yan et al. (2016), which avoids the
problem of separating the scene by depth by factoring
high-dimensional filters into 1D integrals.
are in the far field further away, as shown in Figure 2. Points in the near field, and points behind the focus plane with a temporal anti-aliasing (TAA) pass. The images are finally composited together post-process filtering while parts of the scene deemed inaccurate with post-processing undergo distributed post-process techniques that produce polygonal bokeh shapes based on the silhouette of the camera aperture. McGraw also supports bokeh shapes of non-uniform intensities, including bokeh shapes which are lighter or darker at the rim due to spherical aberration of the lens. Our approach currently generates circular bokeh shapes of uniform intensities but can be extended to produce alternative bokeh shapes such as polygons by changing the shape of our sampling kernel, and bokeh shapes of varying intensities by adjusting the relative weight of samples within the kernel.

Our hybrid DoF technique is novel as we augment conventional post-process approaches with ray tracing, generating more accurate semi-transparencies of foreground geometry in real-time.

3 DESIGN

Our approach in Figure 1 combines post-process based DoF with temporally-accumulated and spatially-reconstructed ray trace based DoF, to produce a hybrid DoF effect that recreates accurate semi-transparencies. Using deferred shading, a Geometry Buffer (G-Buffer) is first produced, together with textures containing other derived information needed for the post-process and ray trace stages. A sharp all-in-focus rasterized image of the scene is also generated. This image subsequently undergoes post-process filtering while parts of the scene deemed inaccurate with post-processing undergo distributed ray tracing augmented with spatio-temporal reconstruction. The images are finally composited together with a temporal anti-aliasing (TAA) pass.

We split our scene into the near field and the far field. Points in the scene in front of the focus plane are in the near field, and points behind the focus plane are in the far field further away, as shown in Figure 2.

We perform this split for both the post-process and ray trace images, in order to merge post-processed colour with ray trace colour on a per-field basis later on.

3.1 Post-Process

For our post-process technique, we adapted the DoF implementation by Jimenez (2014) which uses a gathering approach directly inspired by Sousa (2013) for filtering to produce blur. Following Jimenez the initial rasterized image is downsampled to half its resolution to speed up the filtering process.

3.1.1 Prefilter Pass

For circular bokeh shapes, Jimenez uses a 49-tap 3-ring main filter kernel scaled to the size of the maximum CoC in the tile neighbourhood of the target pixel. However, to fight undersampling, a downsampling 9-tap bilateral prefilter is first applied to fill the gaps of the main filter. We decided to use 81 taps with an additional ring of samples as shown in Figure 3 for better visual quality. Hence, our prefilter kernel has a diameter of 1/8 instead of 1/6 the maximum CoC size as in the original design. In cases where the maximum CoC is too small as most pixels in the neighbourhood are in focus, the size of the prefilter kernel is capped at \( \sqrt{2} \) (diagonal length of 1 pixel) to avoid sampling the same pixel multiple times.

3.1.2 Main Filter Pass

Jimenez performs alpha blending on the foreground and background layers with the normalized alpha of the foreground. However, the implementation result was unsatisfactory as the normalized alpha calculated was too small, producing an overly transparent foreground. Hence, we used a normalized weighted sum of foreground and background contributions for the post-process colour \( v_p \) instead as shown.

\[
 v_p = \sum_{i=1}^{81} D(0,i) \cdot \text{sampleAlpha}(r_i) \cdot v_f + v_b 
\]

In the above equation, \( r_i \) refers to the CoC radius of sample \( i \) while \( v_f \) and \( v_b \) represent the total accumulated colour for the foreground and background respectively. \( D(0,i) \) refers to the comparison of the CoC of sample \( i \) to its distance to the centre tap of the kernel. If the radius of the sample’s CoC is greater than its distance to the kernel centre, the sample contributes to the target pixel’s colour. To combat aliasing, we jitter the camera’s position with pseudorandom number values. We also gather the proportion of samples with high specular values for each pixel to be used to composite ray trace and post-process colour on bright bokeh shapes later on.
3.1.3 Postfilter Pass

Finally, as recommended by Jimenez, we apply a $3 \times 3$ median postfilter at half resolution to upscale the image back to full resolution like in Sousa (2013). The median postfilter, based on a GPU-optimized max-min network flow (Smith, 1996), helps to remove noise from the main pass filtering by rejecting outlier pixels, smoothening out the result.

3.2 Ray Trace

3.2.1 Ray Mask

We shoot a variable number of rays into the scene by creating an adaptive ray mask based on the gradient of surface normals. Employing a selective rendering approach (Chalmers et al., 2006) for better performance, we aim to shoot more rays at edges to create clean semi-transparencies but less at regions with fewer details such as relatively flat surfaces.

Our ray mask utilizes a $5 \times 5$ Sobel convolution kernel to estimate how extreme an edge is. Adopting ideas from Canny Edge Detection (Canny, 1986), we apply a Gaussian filter on the G-Buffer before performing the Sobel operator so as to reduce noise and jaggies along diagonal edges. The Sobel kernel is...
then applied to the filtered G-Buffer at a lower resolution to get an approximate derivative of the gradient associated with each target pixel, based on the depth and surface normal of itself and surrounding pixels which are readily available from rasterization. The depth derivatives capture the separation between overlapping objects where the colour of one object might be uncovered in the other. On the other hand, normal derivatives can detect significant variations in the orientation of primitive faces within objects themselves near their silhouettes, where semi-transparencies are observed in DoF. The per-pixel output of this filter is:

\[ x = (\delta_d + \delta_n) \cdot s, \quad s \in [0, 1] \]  
\[ x_n = \text{saturate} \left( 1 - \frac{1}{x + 1} \right) \]  

Here, \( \delta_d \) and \( \delta_n \) refer to the magnitude of the derivative of depth and surface normals surrounding the pixel respectively, based on the Sobel filter. \( x_n \) refers to the normalized \( x \) and \( s \) is a user-specified variable to scale down the result as it is hard to perform normalization with respect to the entire scene, resulting in the aforementioned compromise.

To account for temporal variation to reduce noise in the output, we also shoot more rays at regions of high variance in luminance as inspired by Schied et al. (2017). Hence, the ray mask is complemented with a temporally-accumulated variance estimate \( \sigma^2 \) explained later in Section 3.2.3. Although this variance is small, it is able to detect edges of foreground objects and specular bokeh shapes. We favour shooting more rays in these regions for a cleaner image via scaling the variance by a large weight of 100000. This amplified variance is then used with \( x_n \) to determine the final ray count as follows.

\[ x_f = \text{saturate} \left( x_n + \sigma^2 \cdot 100000 \right) \cdot m \]  

The value of the large weight was chosen with our observation of the final ray mask generated in relation to our variance as shown in Figure 4. Instead of selectively updating specific pixels like in Dayal et al. (2005), we shoot at least one ray per pixel in the near field but increase this number based on the variance gathered over time for enhanced visual quality.
on the lens to a calculated focus point. We consider the final image as the camera sensor and the position of the camera in the scene as the centre of the lens.

After determining the direction from a pixel on the “sensor” (the image being rendered) to the centre of the lens, we then compute the focus point of this pixel on the focus plane. Then, we take random positions on the lens and spawn rays from those positions towards the focus point. As illustrated in Kraus and Strengert (2007), we take multiple samples within a circle to produce random ray origins within the lens’ area. On edges of foreground objects, some rays will hit the object while others will “go around” and sample the scene behind, yielding the effect of semi-transparent silhouettes of the blurred object in the foreground, out of the zone of focus.

We ray trace at half resolution as a trade-off for speed and upscale later using the same median filter as our post-process stage in Section 3.1.3 helping to reduce sampling noise especially on very bright areas of foreground objects. The ray-traced colours and their respective calculated CoC sizes are then sorted by depth into the near and far field. To have a smooth transition between the near and far field, we split the contribution of each ray trace colour per pixel to each field based on its distance from the separating focus plane. A hit ratio is also stored, which is the number of rays contributing to the near field colour divided by the total rays shot.

3.2.3 Accumulation and Reprojection

To increase our sample count, we use temporal accumulation adapted from TAA (Karis 2014). We accumulate the near and far field ray trace colours over time and use an exponential moving average to blend between history and current frames. By default, we use a high blend factor of 0.95 to stabilize the image. However, to account for movement, we leverage Kraus and Strengert (2007), we take multiple samples within a circle to produce random ray origins within the lens’ area. On edges of foreground objects, some rays will hit the object while others will “go around” and sample the scene behind, yielding the effect of semi-transparent silhouettes of the blurred object in the foreground, out of the zone of focus.

Before spatial reconstruction, the ray trace colour is median filtered (Section 3.1.3), which helps to remove sparse unconverged bokeh shapes formed by small specular highlights, trading accuracy for image quality. For reconstruction, we use a circular kernel to gather the surrounding colour contributions of neighbouring pixels. The kernel is scaled for sampling using the average CoC size of the current frame collected from temporal accumulation, which is also used to determine the mip level or level-of-detail (LOD) for the sampling. Samples with CoC radius smaller than their distance to the target pixel are rejected, similar to the post-process filtering approach as described earlier. Finally, we lerped the original colour and hit ratio of the target pixel with that of its neighbours by clamped variance estimates $b$ to avoid over-blurring in converged regions, as shown in the equation below:

$$b = \text{clamp}(\sigma^2 \cdot 2000, 0, 0.9)$$

In the above equation, we are calculating how aggressive our variable size blur is for the ray-traced output. The variance is scaled by a large weight of 2000 to blur any pixels with a small variance. Once again, this value is chosen based on observation of output as opposed to physically correct rendering.

3.3 Composite

For the final image, we apply the ray trace, post-process and sharp rasterized colours onto pixels based
on their $z$-distances in relation to the zone of focus. To determine the depth range of the zone of focus, we first compute the range for which the CoC size of pixels is less than $\sqrt{2}$. If the CoC of a point is smaller than a "pixel" on our camera sensor (or a sensor cell), it will appear as a single pixel in the final image and can be considered in focus. Hence, we determined that the zone of focus is the set of $z$-values where:

$$\frac{a \cdot f \cdot d}{(a \cdot f + \sqrt{2}(d - f) \cdot \frac{w_i}{w_s})} \leq z \leq \frac{a \cdot f \cdot d}{(a \cdot f - \sqrt{2}(d - f) \cdot \frac{w_i}{w_s})}$$

Here, $a$ refers to the aperture diameter of the camera lens, $f$ its focal length, $d$ the distance between the lens and the focus plane, $w_s$ the sensor’s width in metric units and $w_i$ the image’s width in pixels.

Within the zone of focus, the full resolution unblurred rasterized colour is applied instead of the filtered ray trace or post-process colours upscaled from half resolution. Outside the zone of focus, for near field objects and their silhouettes, we then apply the ray trace colour to form accurate semi-transparent silhouettes. However, for bright bokeh shapes, we favour the post-process over the ray trace colour based on the bokeh shape intensity, i.e., the proportion of samples with high specular values gathered from the main filter pass of the post-process stage. Through this, we minimize noise and ghosting artifacts from the ray trace colour in specular bokeh shapes.

For far field geometry out of the zone of focus, we adaptively blend the ray trace colour with the post-process colour using the hit ratio. If the hit ratio is high, we favour the post-process colour as fewer rays hit the far field. On the other hand, if the hit ratio is low, this means that the number of hits in the far field is comparable to that of the near field, so more ray trace colour is used. However, there are also fewer foreground hits closer to the edges of the ray mask. Hence, when blending ray trace colour with post-process colour, using our hit ratio as-is causes blur discontinuities and tiling artifacts from our ray mask. To minimize them while trying to retain the ray-traced semi-transparencies, we only blend at hit ratios below 0.3 to produce a smooth transition between the ray trace and post-process colours, as illustrated in the formula below. If we bias towards the post-process colours ($>0.3$), we will lose the semi-transparencies rendered by our ray trace pass.

$$h = \text{smoothstep}(0, 0.3, h)$$

3.4 TAA

Fireflies are artifacts appearing due to the sampling of very bright pixels which get spread out during spatial low-pass filtering but are not temporally stable. As the camera moves, the bright spots tend to flicker from one frame to another. This persistent flickering is likely due to the temporal instability of the initial rasterized image. Because of its low-pass filtering stages, post-processed DoF is particularly sensitive to pixel flicker and will tend to spread the small temporally unstable highlights, creating fireflies artifacts.

Following the example from Abadie (2018) to remove flickering bright pixels, we resolve our final image with TAA (Karis, 2014), reprojecting previous frames onto the newest frames. To further stabilize our result, we also apply TAA to the initial rasterized image before filtering, as well as to the image generated after filtering to stabilize camera jitter.

4 IMPLEMENTATION

4.1 Falcor

We used the NVIDIA Falcor real-time rendering framework (Benty et al., 2020) with DirectX 12 backend to utilize ray tracing acceleration and develop our hybrid DoF pipeline. We also made use of Falcor’s graphics techniques library to apply Gaussian blur on our G-Buffer and luminance variance in generating our ray mask, as well as TAA to stabilize our result.

4.2 Scene-Dependent Values

The scenes used for testing our hybrid DoF implementation are The Modern Living Room (Wig42, 2014) and UE4 Sun Temple (Epic Games, 2017). We also tested our approach on Amazon Lumberyard Bistro (Amazon Lumberyard, 2017).

For all 3 scenes, we used $s = 0.8$ for scaling in our ray mask as it worked well to identify edges when coupled with our variance estimation. Increasing the value would bias to shooting more rays even at relatively flat surfaces. For The Modern Living Room (or Pink Room), maximum ray values $m$ of 10 to 20 per pixel worked well. Increasing the number of rays had diminishing returns for the visual quality of bokeh shapes. For Sun Temple and the exterior scene of Amazon Lumberyard Bistro (Bistro Exterior), we had to keep our maximum ray count at 10 to get interactive frame rates for large ray masks. However, as Sun Temple and Bistro Exterior are more complex with textures, any noise observed was less noticeable as compared to Pink Room.

Regarding the depth range for our post-process main filter pass, as compared to 100 feet as suggested by Jimenez, we found that a value of 10 cm worked best for our test scenes due to their relatively close...
geometries. As for our mip sampling in spatial reconstruction, we used a simple clamped linear mapping to determine the LOD to sample from, as illustrated in the formula below, where $c_t$ refers to the temporally-accumulated CoC of each pixel. This linear mapping was devised from our observation of the amount of blur in specular bokeh shapes for our test scenes.

$$lod = \text{clamp}(c_t \cdot 0.05, 0, 3)$$  

(8)

We hope to further simplify these scene-dependent variables for ease of use by artists.

5 RESULTS

5.1 Graphics Quality Comparison

We evaluate our hybrid DoF method (c) against our adaptation of fully post-processed DoF (Jimenez, 2014) without local background reconstruction (a), Unreal Engine 4 DoF (Abadie, 2018) (b) and fully ray-traced DoF (Cook et al., 1984) (d) in this section as well as our demo video (link).

![Figure 6: Semi-transparencies of foreground silhouettes.](image)

Figure 6: Semi-transparencies of foreground silhouettes.

Semi-transparencies are of much better quality with hybrid DoF, as seen in Figure 6. For the adapted post-process DoF, the foreground blur is extended out of the object’s silhouette to overwrite the background colour. However, in hybrid DoF, we can see the background object, specifically, the bottom right corner of the cushion appear along the edge of the cushion in front. This same corner is not visible for UE4.

To quantitatively compare the visual quality of our hybrid result with the ground truth (Cook et al., 1984), we chose a shot of PINK ROOM with very blurred foreground geometry that exhibits highly specular bokeh shapes and semi-transparent silhouettes in Figure 7. When compared to ground truth DoF, increasing the maximum number of rays of hybrid DoF for the shot at relatively low ray counts increases the structural similarity index (SSIM), suggesting that our reconstruction filter might be effective in improving image quality. However, at higher ray counts, there are diminishing returns. At this stage, our technique is also unable to reach ground truth quality even at high ray counts, due to some approximated values used in our post-process stage and composition artifacts.

![Figure 7: Top: reference image at $m = 10$. Bottom: graph of SSIM and ray trace pass timings against ray budget $m$.](image)

5.2 Performance

Using the Falcor API helped speed up implementation by handling the loading of scene assets, setting up the rendering pipeline and creating ray tracing acceleration structures. However, the API hides many low-level details from Direct3D, making it difficult to optimize rendering. Consequently, frame rate figures are not representative of how our algorithm would perform if professionally implemented and properly optimized for games. Nonetheless, we believe that our technique can be adapted and optimized for interactive rendering and motivate further research in this direction. We have achieved relatively interactive frame rates without extensive optimization, validating hybrid rendering as a proof of concept.

Our measurements are taken with the Nsight profiling tool on an Intel Core i7-8700K CPU at 16GB RAM with an NVIDIA GeForce RTX 2080 Ti GPU. The shots used include a background-dominant (BG) wide shot and a foreground-dominant (FG) close-up of PINK ROOM, as well as a mixed (M) medium shot of BISTRO EXTERIOR with different $m$ as shown in Table 1, with their performances in Table 2. In particular, the ray trace pass duration is calculated from the combined GPU timings of the Direct3D API calls for building acceleration structures and dispatching rays.
It can be noted that post-processing performances are on par with implementations in a production engine. As a reference, Unreal Engine achieves 1.59 ms on a GTX 1080 (Abadie, 2018). While the duration of other passes remains relatively constant, the cost of the ray trace pass increases with additional rays shot per pixel except for BG. This is because background geometry is predominantly rendered with post-processing, which means that few rays are traced at all. For M, part of the moped is in the foreground and is ray-traced, while the cushion and parts of the sofa are completely ray-traced for FG. Hence, an increasing $m$ gives a dip in frame rate for FG but not M. The cost of 1 ray for M and FG are 0.04 ms and 0.07 ms respectively. These observations allow us to design content-based adaptive trade-offs between quality and performance, which we defer to future work.

### 5.3 Limitations and Future Work

Although our technique improves the quality of semi-transparencies at the silhouettes of blurry foreground geometry, we acknowledge that it currently might not fare as well as other more efficient state-of-the-art post-processing approaches in the following aspects. We hope to continue working on performance optimizations alongside visual enhancements.

Ghosting artifacts currently appear from temporal accumulation as shown in Figure 8a. Using colour-based neighbourhood clamping to combat ghosting as explained in Karis (2013) reintroduces noise as noted in Schied et al. (2017). While we have reduced the blend factor during motion, ghosting is still not eliminated especially at low frame rates as it takes longer for temporal accumulation to converge to the new colour. Potentially, we could adopt ideas from Schied et al. (2018) which manages to eliminate ghosting artifacts by estimating per-pixel blend factors.

Due to our insufficiently-sized ray mask, tiling artifacts are also observed when foreground objects are too close to the camera as seen in Figure 8b. Ideally, our ray mask should be scaled based on CoC size to account for the sizeable blur of objects close to the camera. Hence, for our technique, we could scale our ray mask by the maximum CoC in the neighbourhood.

With 1 sample per pixel, noise generated is inherently difficult to remove. Adopting a final blur like Barre-Brisebois et al. (2019) for reflections resulted in a loss of detail in semi-transparent areas. However, considering that we only ray trace within a ray mask, using a variable number of rays is a good compromise for better image quality.

As many post-process effects remain to be enhanced with ray tracing, we are also exploring hybrid
Table 2: Pass durations (in ms) and frame rates.

| Shot          | m  | 1   | 30  | 50  |
|---------------|----|-----|-----|-----|
| Rasterization | BG | 1.70| 1.72| 1.70|
|               | M  | 2.07| 2.05| 2.04|
|               | FG | 1.90| 1.89| 1.89|
| Post-Process  | BG | 1.43| 1.44| 1.42|
|               | M  | 1.63| 1.62| 1.69|
|               | FG | 1.68| 1.67| 1.66|
| G-Buffer & $\sigma^2$ Blur | BG | 0.64| 0.64| 0.65|
|               | M  | 0.66| 0.66| 0.65|
|               | FG | 0.65| 0.65| 0.64|
| Ray Trace     | BG | 0.18| 0.19| 0.18|
|               | M  | 0.26| 0.36| 0.28|
|               | FG | 0.40| 0.28| 0.35|
| Accumulation  | BG | 0.60| 0.60| 0.60|
|               | M  | 0.60| 0.60| 0.60|
|               | FG | 0.61| 0.61| 0.61|
| Median        | BG | 0.35| 0.34| 0.34|
|               | M  | 0.33| 0.34| 0.34|
|               | FG | 0.34| 0.34| 0.34|
| Recon-Composite | BG | 0.42| 0.42| 0.42|
|                | M  | 0.81| 0.79| 0.81|
|                | FG | 1.42| 1.40| 1.42|
| Final TAA     | BG | 0.53| 0.53| 0.53|
|               | M  | 0.53| 0.53| 0.53|
|               | FG | 0.53| 0.53| 0.53|
| Others        | BG | 0.64| 0.64| 0.66|
|               | M  | 0.64| 0.61| 0.65|
|               | FG | 0.64| 0.62| 0.65|
| Our Pass      | BG | 2.19| 2.19| 2.19|
|               | M  | 2.66| 3.75| 4.49|
|               | FG | 3.42| 5.08| 6.26|
| Total Duration| BG | 6.49| 6.52| 6.50|
|               | M  | 7.53| 8.56| 9.40|
|               | FG | 8.17| 9.79| 10.99|
| Frame Rate    | BG | 181 | 179 | 180 |
|               | M  | 96  | 97  | 97  |
|               | FG | 146 | 122 | 110 |

rendering for motion blur. Post-processed motion blur poses similar issues of semi-transparencies. Hence, we are also investigating the use of ray tracing to uncover true background information behind motion-blurred foreground objects (Tan et al. [2020b]).

6 CONCLUSION

We present a hybrid real-time rendering technique for the DoF effect in games. Our ray trace pass attains better image quality by rendering more accurate semi-transparencies with minimal artist overhead. Additionally, our ray mask and adaptive ray count, even when unoptimized, allow us to achieve relatively interactive frame rates. In future, we hope to augment and incorporate other effects like motion blur into our hybrid real-time rendering pipeline. Our hybrid rendering engine will be open-sourced for the benefit of the research community and the industry.

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