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C. E. Catalano and A. D. Parakkat (Editors)

Revisiting Analog Stereoscopic Film

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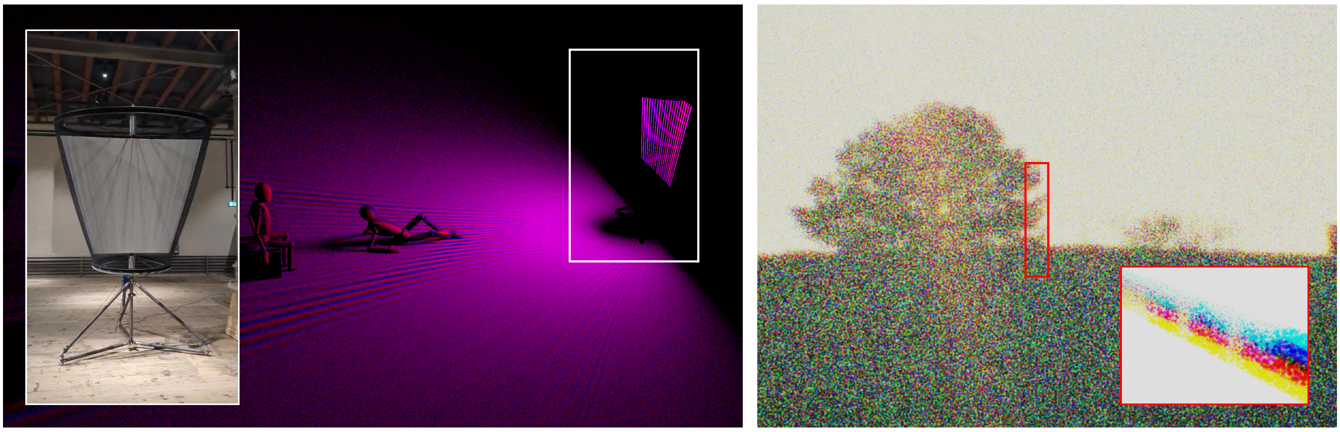

Figure 1: *On the left side a picture (inset) of the* cyclostéréoscope*, an autostereoscopic display, and the corresponding simulation of its viewing zones (white rectangle) is shown in red and blue. On the right, a volumetric visualization and simulation of analog film and its corresponding layer structure (inset, corresponding to the area covered by the red rectangle) is shown.*

Abstract

We present approaches for the simulation of an analog autostereoscopic (glasses-free) display and the visualization of analog color film at micro scales. These techniques were developed during an artistic research project and the creation of an accompanying art installation, which exhibits an analog stereo short film projected on a re-creation of a cyclostéréoscope, a historic device developed around 1952. We describe how computer graphics helped to understand the cyclostéréoscope, supported its physical re-creation, and enabled the visualization of the projection and material structure of analog film using physically based Monte Carlo light simulation.

CCS Concepts

• ***Applied computing*** → ***Media arts;*** • ***Computing methodologies*** → *Animation;* ***Rendering;*** • ***Human-centered computing*** → ***Visualization systems and tools;*** • ***Hardware*** → *Displays and imagers;*

1. Introduction

In this research, we explore and discuss approaches for the simulation of an analog autostereoscopic display and the visualization of analog film developed during an interdisciplinary artistic research project resulting in an analog stereo short film called *Revolving Rounds* [Lur24], This project was a collaboration of people from different disciplines, i.e., architecture, dance, film, fabrication, and computer science. One goal was to create an analog stereo short film in which an audience could perceive the microscopic structure and projection of the analog film in its three-dimensional form. In addition, some form of stereo display or projection was needed to allow the audience to view this analog film in stereo (3D). For this purpose, an art installation was developed that includes a (re-)construction of a mechanical stereoscopic display called *cyclostéréoscope*, on which an analog stereo short film can be shown.

One part of this film was envisioned to include a sequence in which the camera continuously moves into the projected analog film substrate and passes through it. Analog color film consists of multiple layers of microscopic colored dye clouds, which form the final image [KKM*00, Rog07]. Filming this sequence with con-

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ventional cameras is highly impractical. It was, therefore, decided to create this sequence digitally by simulation and combine it with the analog footage. For this, the analog stereo film was scanned, and the digitally created sequence was added before the edited film was developed again back onto analog film. This final analog version was then projected on the custom-built *cyclostéréoscope*.

In this paper, we describe in particular the development and fabrication of the autostereoscopic (glasses-free) projection, as well as the creation of the 35mm analog stereo short film featuring a closeup of a pea plant as well as the projection system itself. In the digitally created part of the film, the viewer should perceive the microscopic structure of the analog film in its 3D form by passing through the analog film substrate. Filming this sequence using conventional cameras would be highly impractical, requiring microscopic high-speed cameras. Therefore, we created the sequence digitally by simulation and combined it with the analog footage. To enable visitors to perceive the finished analog film in stereo (3D), a mechanical stereoscopic (glasses-free) display called *cyclostéréoscope*, an old technology developed around 1952 [Sav52], was (re-)constructed.

Our paper makes the following contributions:

- A method for simulating a *cyclostéréoscope* and visualizing the corresponding viewing zones for stereo vision.
- An approach for the volumetric visualization of the microstructure of the analog color film and its layers.
- A real-world example in which these approaches were used in an artistic research project in the creation of an analog 35mm stereo short film and the construction of a *cyclostéréoscope* for a corresponding art installation.

Specifically, we will discuss how physically based Monte Carlo (MC) light simulation helped to understand and plan the development and construction of the *cyclostéréoscope* (in Section 2) and enabled a unique perspective on the layers and structure of the analog color film and its projection (in Section 3).

2. Cyclo-Stéréoscope

Perceiving visual depth is largely due to the slight parallax (offset) between the two images that our eyes see, which our brain interprets as depth [PI17]. Therefore, to show a film in stereo or 3D (with depth), one has to record using two cameras with a horizontal offset between them and then show the film in a way that ensures that the recording of the left and right cameras is only seen by the corresponding left and right eye [Tri16].

Although there exist advanced glasses-free stereo displays [HQC22], stereo is commonly accomplished by shutter or polarized glasses [CL13], which block one of the two simultaneously displayed images to allow each eye only to see the corresponding left or right image. In the early days of analog film, polarized glasses were usually used [Kin13], which achieve this separation via polarizing filters. However, there were also glasses-free displays developed [Fun12], one of which is called *cyclostéréoscope* [Sav52], a mechanical auto-stereoscopic display developed around 1952.

This device achieves the separation between the images for the left and right eye via a rotating parallax barrier (conical blocking screen with vertical slits) placed around a projection screen (see Figure 2) and rotated so that the individual slits become less perceptible due to motion blur. Two film projectors shine light through this barrier onto the screen inside, simultaneously displaying both the left and the right stereo image in an interleaved pattern (see Figure 3). Blocking the projected light and the view onto the screen through the vertical slits in the barrier creates alternating zones in the space in front of the *cyclostéréoscope* where either the left or right image is visible. This is visualized in Figure 6 using red and blue colors for the projection.

Figure 2: *Pictures of the first two* cyclostéréoscope *prototypes (cylindrical and conical) in the workshop (left) and the final and bigger conical version in the art installation (right).*

The geometry of the vertical slits, the top and bottom radii of the parallax barrier, as well as the distance of the two projectors to the screen and the offset of both projectors, determine the size and position of the viewing zones in space. By careful adjustment, it is possible to create a configuration of viewing zones in which observers can find locations where both eyes are aligned in such a way that they exclusively see the corresponding left or right stereo image, thus achieving glasses-free 3D stereo and perception of depth in a film projected onto the screen. The theoretically optimal viewing zones are located on the line connecting the projection center with the virtual tip of the conical parallax barrier, as illustrated in Figure 4.

2.1. Recreation and Development

To build the *cyclostéréoscope*, we first needed to understand it and how the viewing zones emerged from its geometry and the relationship to the projectors. Only limited information was available, e.g., photos, technical descriptions [Blu13], and old film footage. However, it was unclear if some crucial details were missing that would be relevant for construction and operation. The original *cyclostéréoscope* used a conical design to support viewing zones for

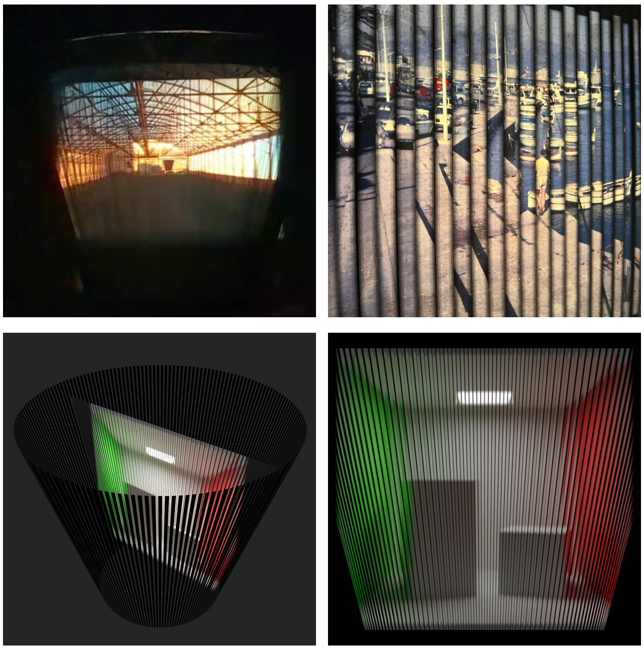


Figure 3: *The top row shows a real picture of the second prototype of the built conical* cyclostéréoscope *(left) and a closeup of the screen of the first cylindrical prototype (right). The second row shows the simulation and rendering of the conical* cyclostéréoscope *(left) and the corresponding closeup of the screen where the interleaved right and left stereo images are visible (right).*

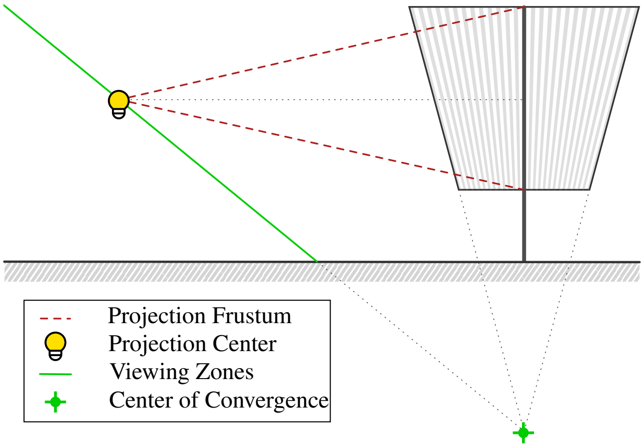


Figure 4: *Conceptual 2D illustration (side view) of a* cyclostéréoscope. *The optimal viewing zones are located on a line (green) connecting the projection center and the virtual tip (center of convergence) of the parallax barrierer's cone. Starting from this line, the optimal viewing zones in 3D form a more complex surface, as illustrated in Figure 6.*

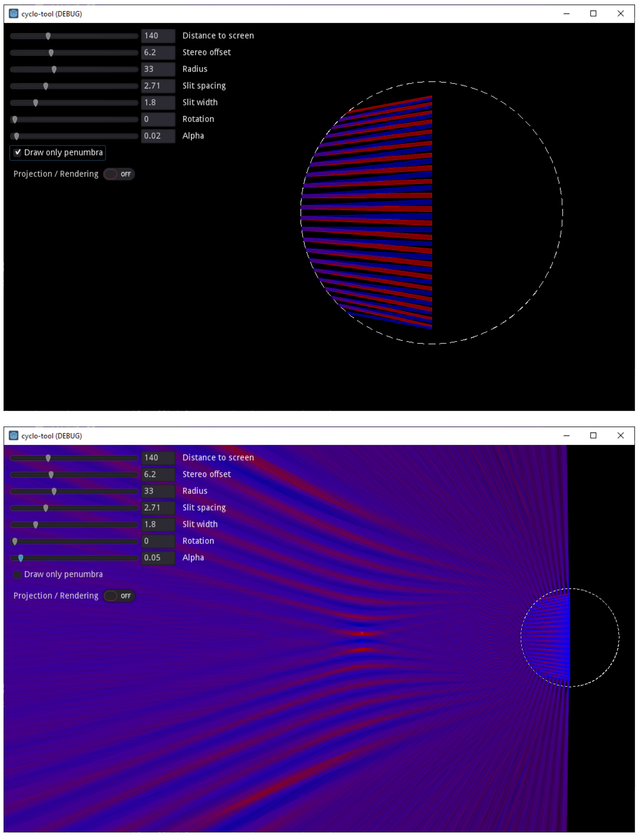


Figure 5: *The 2D viewing zone visualization tool simulates light paths from the projector through the barrier (top) and reflection from the screen back through the barrier again (bottom). The light from the projectors is represented by the two colors, red and blue, to highlight areas where only one of the projections or both are visible.*

an auditorium. Our initial prototype used a cylindrical shape to make it easier to build and understand.

Cylindrical Version

At this stage, we developed a parameterized graphical 2D tool to help understand the geometric relationships between screen and projector positions, the dimensions of the parallax barrier, and the emerging viewing zones. Figure 5 shows the interface and visual representation of the areas that are illuminated by the light of each projector. The parameters can be adjusted to get an understanding of their influence on the structure of the emerging viewing zones.

This 2D simulation of these viewing zones is rendered in the rasterization-based game engine *Godot* [The23]. The visualization is computed by alpha-blending of polygons, which represent the light emanating from the projectors, which passes through the parallax barrier and is reflected out by the diffuse projection screen. In zones of adjacent uniform (red or blue) color, glasses-free stereovision is possible, since here, each eye of a viewer can see one of the stereo images exclusively. In all other areas light (images) from both projectors strongly overlap and mix, making stereo vision impossible.

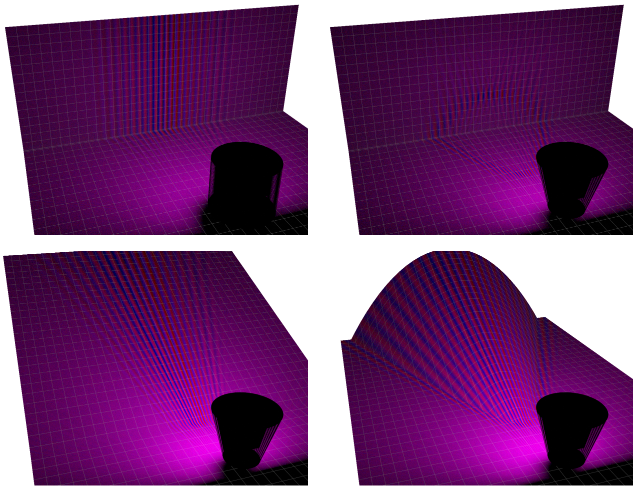


Figure 6: *Here, we visualize the distribution of viewing zones. Most optimal viewing zones are distributed in a vertical plane through the projection center (top left) for a cylindrical parallax barrier. A conical barrier has a more complex distribution (top right). Using a plane aligned with the line between the projection center and the tip of the cone, similar to an auditorium, we can already see areas of suitable viewing zones (bottom left). The complete region of viewing zones can be visualized by using a parabolic surface (bottom right).*

Conical Version

We applied lessons learned from the cylindrical prototype to construct a conical version. To further understand the more complex setup, we used physically based MC light simulation, i.e., path tracing, to simulate the viewing zones of a conical barrier, see Figure 6.

While the cylindrical shape exhibits most of the optimal viewing zones in a vertical plane at the distance of the projectors, A conical shape results in a more complex distribution of viewing zones, i.e., on different levels above the ground and at different distances from the screen. Here, the shape is a curved surface that sweeps along the line between the projection center, i.e., the point between the optical centers of the projectors, and the tip of the barrier's cone (green line in Figure 4).

The 3D simulations and visualization of the *cyclostéréoscope* are done in *Blender* [Ble23]. The projection setup (shown in Figure 7) includes projector location, screen, and the conical barrier, which are procedurally generated using *geometry nodes* for interactive adjustment of geometric parameters. We use path tracing via Blender's internal rendering engine *Cycles* to render the scene and visualize the viewing zones since it is able to compute accurate indirect lighting effects.

3. Analog Stereo Film

The conceptual idea behind the film and art installation, as described at the beginning of Section 1, also planned to move beyond what conventional cameras can resolve, visualizing the structure of analog film, and its projection.

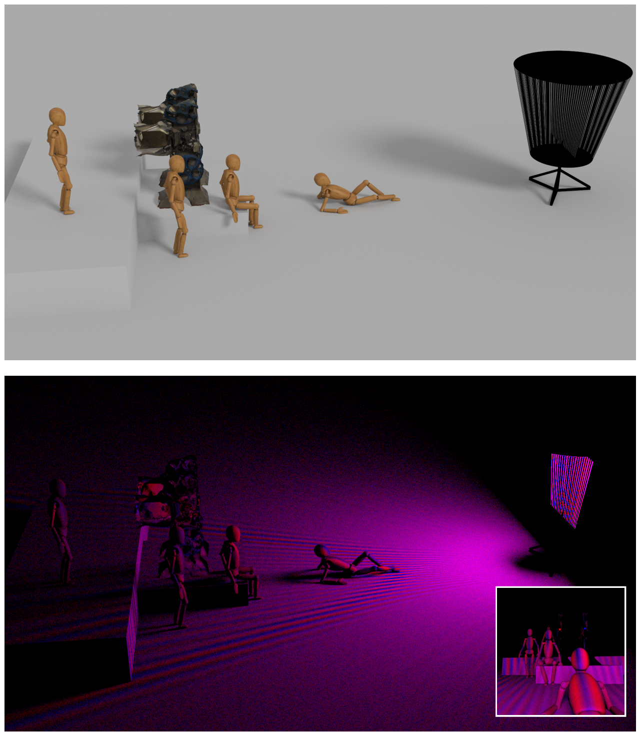


Figure 7: *The physically-based MC light simulation reveals the location and shape of the viewing zones. The top image provides an overview of the virtual prototyping scene, and the lower image shows the scene illuminated only using red and blue light from the projectors to illustrate the viewing zones.*

In this sequence, the camera moves closer and into the projected analog film until the individual layers and fundamental components of the analog color film become visible, i.e., layers of individually colored dye clouds, and see the shadow of the projector's shutter blade moving across the film, and time slowing down. It is highly impractical, if not impossible, to film this using conventional analog cameras. Therefore, we created this sequence using computer animation and physically based MC rendering, i.e. volumetric path tracing, allowing us to simulate the absorption and scattering of light inside the dye clouds layers of analog film.

3.1. Visualization

When an analog film is projected, white light from the projector passes through colored layers inside the film, i.e., cyan, magenta, and yellow (CMY). In these layers, parts of the light spectrum are absorbed (filtered) depending on the density of each layer, which can be modeled by subtractive CMY color mixing. Consequently, to recreate what happens in actual analog film, we need to decompose an existing frame of analog film into these three color layers and simulate the absorption and scattering of light. For this, we created a virtual scene in *Blender* [Ble23], which included a spotlight illuminating the film from the back and the rotating shutter blade in between to simulate the 48 Hz black phases during projection.

To model the film substrate and its color layers we use a volume

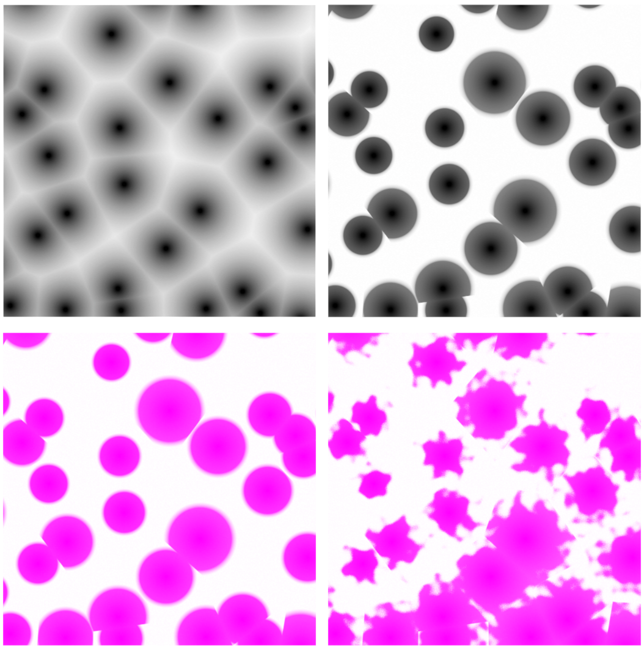


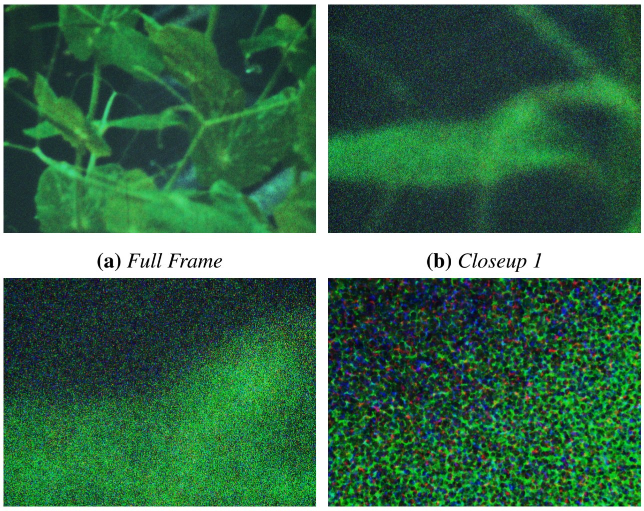
Figure 8: *Conceptual illustration of the dye cloud generation in the film's material shader using a 2D example of a single-colored dye cloud layer. Starting with a Voronoi texture representing the distance to each cell's center (top left), this distance is then clamped at different values (proportional to s_L, see Equation 1) to obtain circular areas of specific sizes (top right). Then, the layer color is assigned to these areas (bottom left), and additional random factors modulate the clamping value to randomize the area's shape for a more cloud-like appearance (bottom right).*

with a custom material (shader). To render it, we use volumetric path tracing using Blender's internal rendering engine *Cycles* since this enables us to simulate the intricate absorption and indirect scattering of light inside the dye clouds of the different color layers. To create the individual layers, we use sequences from the original analog footage, and use the (RGB) color of its individual frames to modulate the density and (CMY) color of the volume. This is illustrated in Figure S2 in the supplemental. To simulate the CMY color mixing, we vary the density inside the different layers by modulating the size of the dye clouds. This scaling factor s_L is computed as

$$s_L = \left\| \left(1 - \begin{bmatrix} R_L \\ G_L \\ B_L \end{bmatrix} \right) * \begin{bmatrix} R_I \\ G_I \\ B_I \end{bmatrix} \right\| \quad (1)$$

where the RGB_L vector represents the layer color (CMY) and the RGB_I vector the color of the input frame (RGB). This effectively scales the dye clouds in each layer so that the structure and color of the original input frame are recreated via CMY color mixing. i.e., the absorption of light illuminating the film. The generation of the randomly distributed dye clouds is explained in Figure 8.

We used this approach to render the sequence where the camera moves closer toward the film and through the different color layers. The beginning shows a scene with a pea plant – see Figure 9 –



(a) *Full Frame* **(b)** *Closeup 1*

(c) *Closeup 2* **(d)** *Closeup 3*

Figure 9: *Top-down view onto the dye-cloud volume at different distances to the film's surface, using one frame of the plant sequence.*

and the end, in which the camera moves out again on the other side, shows a field – see Figure 10. These figures illustrate how our approach enables us to recreate the analog image and to seamlessly move close to the image until the individual dye clouds become visible.

The slow-motion effect was achieved by creating a custom plugin for *Blender* that maps real time to animation time and changes the camera's shutter timing accordingly to achieve a consistent motion-blur effect.

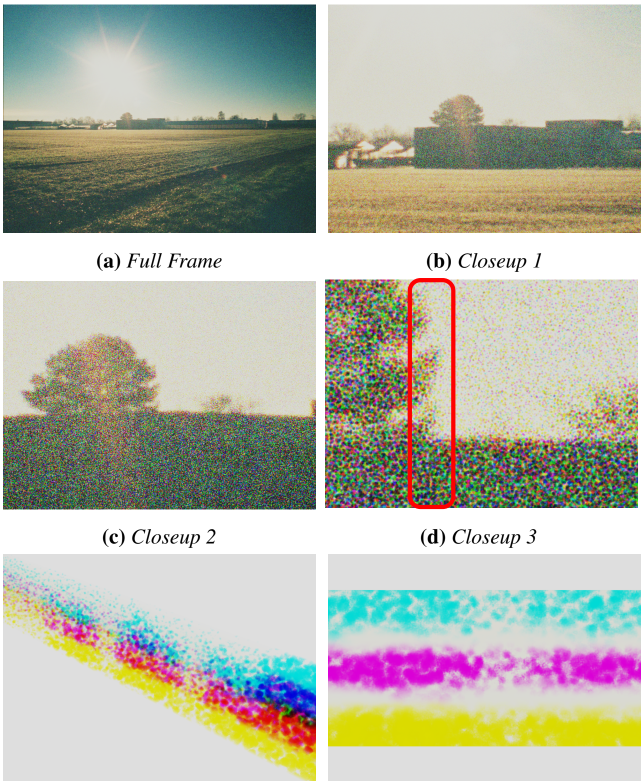
4. Discussion

Cyclostéréoscope construction. The digital simulation facilitated the understanding and construction of the *cyclostéréoscope*. By using physically based rendering, we could, within the limits of the simulation, predict the viewing zones. It also enabled testing of different parameter configurations virtually, and gaining an intuition before the construction of the *cyclostéréoscope*.

However, some aspects were only revealed after construction and were not covered by the simulation. One such important aspect concerns the rotation of the *cyclostéréoscope*. Live testing showed that (the initially planned) back projection is impossible. Furthermore, it revealed the interplay of the 48 Hz of the film projection, the rotation speed of the parallax barrier, and the spacing of the slits in the barrier, as well as its influence on the quality of the perceived stereo effect.

Rendered film sequence. The sequence of moving the camera through the layers of the analog color film required a digital render process using physically based light simulation.

However, our simulation is only a conceptual approximation since it does not simulate all layers of an analog film, and geometric, material, or illumination parameters were chosen manually



(a) *Full Frame* **(b)** *Closeup 1* **(c)** *Closeup 2* **(d)** *Closeup 3* **(e)** *Closeup 3, Slice* **(f)** *Closeup 3, Slice, Side View*

Figure 10: *Top-down view onto the dye-cloud volume at different distances to the film's surface, using one frame of the field sequence. The two bottom images show a closeup of a small volumetric slice through the film's layers corresponding to the area marked by the red rectangle, revealing the three color layers and varying dye cloud sizes and density, which is modulated by the frame's source input image.*

and are not based on exact measurements. Therefore, our approach serves more as a visualization of the three color layers as well as the concept of image formation via subtractive color filtering. Furthermore, adjusting the illumination and the parameters of the volumetric material shader to exactly match the input image in color, contrast, and brightness turned out to be difficult. This is partly because we had to introduce a slight amount of scattering in the volumetric material such that the light from the spotlight became visible to the camera. This scattering is more realistic but works against the ideal model of subtractive color mixing used to scale the dye clouds and, therefore, changes the final color. Therefore, we chose to use a simpler translucent shader when viewing the film from afar, i.e., when the whole image is visible, and only transition to the full volumetric shader when the camera is close to the film, enabling a smooth transition from the analog film footage to the rendering.

5. Conclusion

In this paper, we presented our approaches for the simulation of an auto-stereoscopic display, called *cyclostéréoscope*, and for the visualization of the layer structure of the analog color film. We discussed how these were used to construct a functional recreation of the *cyclostéréoscope* and to create the analog stereo film, which included a digitally rendered sequence in which the camera virtually passed through the analog film substrate and its layers. These physically based light simulations allowed the development of an art installation in which this analog stereo film is projected onto the *cyclostéréoscope*, enabling the viewer to see the analog short film in 3D without any glasses.

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