ABSTRACT
A major challenge in a simulator design is to make multiple projectors acting as one. There are currently two different approaches to this problem. One is to accept that the seams can be visible, and as such going to facet without overlap, while the other one blends each projector image into its neighbours in order to eliminate the visibility of the different channels.

This challenge exists since the day where one needed to make a visual system which could not be done via a single projector. Quickly, they found out that multiple difficulties awaited them. These included visibility of a seam between projectors, color and brightness mismatch, geometry discontinuities...

For most, geometry discontinuities could be tackled with proper image processing. The visibility of the seams could be removed by adding the overlap (blendzone) between the projectors.

Color and brightness mismatch could be tweaked away somehow, mainly electronically, with the finding that a larger blendzone helped in hiding this mismatch.

Out of these elements, this paper will focus on the means of realizing the blendzone, and in particular the technologies referred to as optical blending, used to obtain perfect brightness crossfading during night scenes.

We will elaborate on the relevant optical background information to understand the strength and weaknesses of each option. It will introduce a not-yet used technology which should overcome the limitations of the other ones.

INTRODUCTION
Any simulator manufacturer aims to remove the multichannel junction artefacts within the constraints imposed for a specific project or simulator type. The implementation varies from one to the other, but as the physics behind is the same for all, they converge to the same principles.

One of the challenging points for such is the brightness adjustment over the junction during night scenes.

Due to the limitation of modern projectors not being able to produce absolute black, for most cases there is a need of using physical elements in the optical path to create the proper crossfading during night scenes.

After highlighting the reasons why these systems are so sensitive to this brightness change, this paper will state the goal of blending technologies. It will then provide some optical background in order to have sufficient understanding of the challenges, to finally review the existing and upcoming optical blending technologies.

BACKGROUND
Optimizing technologies for a multi-channel display cannot be done without understanding both why we see artefacts and what we want to reach. On the reasons why we see artefacts, one could just answer that we see them because they are there. On the other hand, any commercial display has some significant brightness and color non-uniformities if measured but it goes unnoticed. These non-uniformities are often larger than what a non-optimized multichannel system would have at the channel junction.

The key point is that the brain focuses on changes, the faster a change is, the more noticeable it becomes. This is valid for temporal changes as well as spatial changes. Back to our commercial display, the non-uniformities on these are spread over the whole display, and therefore appear as a “slow change”. In our multichannel displays, the change from one channel to the other one happens on a much smaller area, being the either a line or the blendzone.

It becomes immediately obvious that any difference between the two touching channel will be seen as a very abrupt change, and as such very visible.

When it comes to brightness level, another major element comes into play is the screen type. Depending its properties (gain curve, Half gain angle…) the brightness and brightness variations seen by the user will be different.
As the screen type mainly impacts the design of the blend rather than the blend technology itself, this will not be further detailed in this paper.
More generally, while multiple elements lead to a better or worse blendzone on the screen, this paper focuses on the technologies used to physically create brightness crossfading, so the physical implementation of the blendzone design.
The design of the blendzone itself (including its position, width, linearity…) is of course a major step in getting good blendzones, but is not discussed here.

**BLEND TECHNOLOGIES REQUIREMENTS**

In order to properly analyse the various technologies we should first of all set what the design goal of such technology are.

**Blending requirements**
Whatever the blending technic considered, we can split the blend pattern in 3 areas:
- Transparent area, the main image area for this channel
- Transition area, the actual blendzone going from the transparent to the blocking area
- Blocking area, the place where this channel should be blocked as this would result in projecting on another channel’s main image area

![Figure 1: Example blend](image)

The key point when looking for ideal characteristics is that the blend pattern task is only to take care of the brightness cross-fading, nothing more, nothing less.
Indeed, when one perfectly matches 2 channels projecting on the same area, the geometry and the color of the overlap can in theory be as good as each of them individually, while the brightness is doubled.
Obviously, and as discussed before, this smooth brightness transition will allow for the brain to tolerate bigger deviations on color and geometry.
This said, our blend technology requirements are relatively straightforward.

**Transparent / main image area**
This is area where only the concerned channel projects. This area should stay untouched, without any impact on image quality.

**Transition area**
This is the overlap area; the transmissivity of the blend pattern should gradually go from 100% to 0%, leaving color, geometry, convergence, sharpness… untouched.
As one transition area will have to counter-match the transition area of the neighboring channels, the transition as it gets on the screen needs to be very well controlled.

**Blocking area**
This one should fully block any light, just like if the projector would be shutdown.

**ELECTRONIC BLENDING**

Electronic blending stands for blending technics where the image is altered via image processing algorithm before reaching the imaging device (DMD, LCoS…). Nowadays this can easily be done in the Image Generators, the projectors themselves or in dedicated hardware often referred to as warpboxes.
This has the obvious benefit that there is nothing added to the optical path, limiting risk of image degradation, but also has some drawbacks, depending on the region.
Electronic blending is not discussed in detail in this paper, but the main relevant drawback for us is that modern projectors are not able to project real black, it is always a small amount of light. As such, when displaying a full black image with Electronic blending these small amounts of light add up and clearly outline the overlap areas. This effect is the main reason for using optical blending.
It has to be mentioned that there exist projectors today using special image modulator in order to reach significantly higher contrast and so allowing good electronic blending by night. As these projectors are a minority and have other drawback preventing them from being used in all systems, the topic of optical blending in general is still valid.

**OPTICAL BLENDING**

**Some Optical Background**

**Projection light path**
In order to cope with the double black of electronic
blending, optical blending has been developed. In the scope of this paper, we will refer with optical blending as all technics using a physical element in the optical path with the purpose of creating the so desired brightness cross-fading on screen.

In order to understand the optical blending challenges, one need to be acquainted with the way the projector light gets on the screen.

- The light coming from the projection lens to the screen can be drawn as originating at the lens exit pupil, and going to the screen in a straight line.
- Ideally the exit pupil can be approximated as a disk being uniformly filled with all the light coming out of the projector at a given moment.
- Every single point on the screen receives rays coming from the entire surface of the exit pupil

For modern projectors the exit pupil diameter is usually below 1cm.
As such every point originates at the same location (exit pupil) and with the same size (exit pupil diameter) to finally and ends as a point at their respective location on the screen. One can immediately spot that adjusting the focus of the projector means making sure that it indeed is a point at the distance of the screen.

![Figure 2: Projector to screen light path](image)

As our blending element will be placed close to the projector, each point is still a large disk, so the blending element is out of focus. The direct consequence is that the shape of the blending element is not directly replicated on the screen. Mathematically, the blend pattern visible on screen is a convolution of the blend element and of the disk as it is at the location of the blend element. Said otherwise, every point of the screen only gets the amount of brightness from the exit pupil which has not been blocked along the way.

If we approximate the blend element as a straight piece of light blocking material we get the following 3 cases:
- The dot brightness is untouched
- The dot brightness is partially blocked
- The dot is totally blocked

An important remark though, the assumption taken above that the exit pupil is a uniformly filled disk is far from being the reality. Below is an example of a projector exit pupil.

![Figure 3: Hard edge effect](image)

One can see that neither the brightness nor the color is uniform. This is valid for any projector, but of course always with different aspect depending on the internal optical path of the projector.
Due to these non-uniformities, the result of the convolution will not just be a sweeping average of the blendzone, but may increase the visibility of the blend pattern on the screen.

**Diffraction & Interference patterns**

Down to somewhat deeper but simplified optical principles.
Mind it is not the purpose in this chapter to provide detailed calculations and physics law on the diffraction phenomenon, but only to lay out the key elements which will come into play for our analysis of various optical blending technologies.

Whenever some light hits an object, part of this energy is absorbed and part of it is scattered. Close to us, the light our eyes receive from our simulator screen is the light scattered by the screen (in this specific case, diffused).
When a beam of light hits an edge, one can easily get that some amount of light is scattered “backward” and some
“forward” (as thinking of light as particles).
To the application of projection, this forward light is an amount of light which will end up at a different place on the screen than its initial intent, and will deteriorate the image.
This effect alone on a single edge is for most of it not so limiting in our application, however this brings a second effect.
If we gather in a small area a lot of these edges, the effect is obviously multiplied. If these edges happen to be “sufficiently numerous” and “sufficiently ordered”, all these scattered light will manage to add up, in best case degrading the image quality, in worst case recreate shifted copies of the image (ghost images).
We are not going to attempt quantifying here these concepts as this would bring in many more factors than what can be covered here, so it will be easier to take a couple of example:
- A narrow tip yields two edges well ordained (almost parallel edges)

Figure 5: Narrow angle
- A rounded tip does not have the thinnest part, with the two edges very close

Figure 6: with rounded tip
- A uniform grey area printed by a regular printer is made of thousands of tiny black dots printed according to a grid, so in essence a high number of small geometry well ordained

This last example is the easiest one to test, printing a grey area on a transparent plastic and placing it in front of a projector will immediately create very visible ghost images.

For the sake of completeness, we should add that to see this effect, the same image (point) has to go through this ordained pattern. In our projector, our complete exit pupil represents the same image point, so we do have each single image point going through a somewhat large area of the blend pattern.

As a summary we could say, the more diffracting edges we have the higher intensity will be diffracted, and the more ordained they are the more noticeable will be the effect.

Optical blending families

Looking at the physical element to place in the optical path, we find multiple families:
1. Hard-edge
Hard-edge blends usually refer to the use of “straight” light blocking material replicating the expected shape of the blendzone.
The material can be almost anything.
One example is the version used by Barco in the past. A piece of rubber was held by adjustment screws in order to create the correct blend shape. Adjusting the screws would bend the rubber in order to reach the required shape.
Let’s check our three blend areas with such technology:
Main image area
There is physically nothing here, so this is the ideal case.
Transition area
Here the only flexibility is in the shape of the blendzone, but the transition from 100% to 0% is totally uncontrolled, as the only element introducing a transition is the exit pupil size and uniformity, on which the system designer has no control. As such, proper matching of the complementary blends is not possible.
This kind of technic is then used in combination of electronic blending, with the only purpose being to smoothen the transition from single black to double black in order to decrease its noticeability, without the intent of actually removing the double black in the overlap area.
As the exit pupil can also have color non-uniformity, one can guess that such technic can also outline colored patterns on the screen.
These effects will dominate the diffraction effect mentioned earlier.
Blocking area
As we can use a thick material, totally blocking the light in the blocking area is not a difficulty.
2. Comb/Saw tooth
This is an improvement of the previous one. We use here the same concept, but we control the transition by replacing the straight line with a comb or fine saw tooth pattern.
While performing the optical convolution, the exit pupil will smoothen out the saw tooth pattern, starting with only the tips to progressively end in the full blocking area.
One can immediately recognize that the main area and blocking area will have the same benefit as the hard-edge technic while we now have some more control on the transition area.
On the other hand, it now becomes impossible to have an
on-site adjustable version, as the teeth need precise engineering and cutting.

The teeth design itself also has some strong limitations:

- A blend with an angle has no design solution
- It needs to be physically manufacturable
- They need to be small enough so that the convolution is sufficient to blur them out, as noticing them on the screen would be unacceptable
- As we reduce them to improve visibility we introduce diffraction problems

Improving the diffraction visibility means avoiding order, however introducing randomization also means introducing bigger and smaller geometries, reducing again the available playground between a few big visible geometries and numerous small diffracting geometries.

Note that one element used is to reduce the width of the blendzone. If the comb pattern is thinner than the exit pupil dimension, the diffraction will see a smaller amount of edges, so will be improved, without affecting the pattern visibility. Obviously this limits the amount of control we have on the transition again as this means we accept that the dominant transition factor is again the exit pupil uniformity.

Adding both the design and manufacturing constraints of such saw-tooth makes their use usually limited to relatively simple systems with up to 2 blendzones per channel in order to reach acceptable blending.

3. Transparent substrate

The last optical blending technology approach here is the most flexible one. This one uses a transparent substrate covering the full image size, and “mark” the blend pattern on it. We will call this marked substrate a blend plate.

Capabilities and limitations of these blendplates varies very much with the manufacturing process used, as such these will be detailed one by one in the next chapter, however the common element is that this is now the first technology which has a physical element in the main image area, and so potentially impacting the main image.

4. Motorized blending

Before going further, one should mention that the quality of the blend is far more critical in day scenes than in night scenes due to the lower sensitivity of the eye with in low light environment. As such technologies yielding limited quality blending are often only used by night with some mechanical switching mechanism, combined with electronic blending by day.

The benefits of motorized blending are real but are not discussed here as blendplates are still needed for a lot of configurations.

**BLEND PLATES**

**Substrates**

In case of blendplates, as the substrate is present in the main image area, it must be at least highly transmissive. In order to do so one can use a very thin material, or a thicker very transmissive material.

This said, the two immediate examples coming to mind are films and glass plates.

The transmissivity of the substrate impacts not only the brightness level, but can also impact the checkerboard contrast of a projector; if the substrate scatters light, the white squares will impact the black squares.

**Films**

Films can be of different type, but typically offer the benefit of being cost effective. They obviously have the challenge of limited flatness, which may impact the quality of the image, depending on its refraction index.

High brightness levels may also impact the lifetime of the film.

**Glass**

Glass is commonly used in high quality optical components because of its very good characteristics. It is naturally highly transmissive, can be bought in very flat pieces and even coated with Anti-Refecion coatings to easily reach 98% transmission.

It can also be used to improve the film substrate by sandwiching the film between glass plates, creating an optical stack with better performances than the film alone.

The main challenge with glass is to find a proper marking technology to mark directly on it.

**Marking Algorithm**

As discussed earlier in this paper, in order to have a good control on the brightness crossfading our blend pattern needs to exhibit a continuous transition from black to transparent.

In order to have the in between “gray” there are two main possibilities, either to use dithering with a full black / full transparent marking technic and then relying again on the convolution to smoothen the dithering out, or to use a marking technic which can actually produce gray.

**Dithering**

Using dithering is basically the improvement from the comb/saw tooth pattern. Indeed, now that we have a transparent substrate to put the marking on, the shapes
possibilities are numerous.
As such there is now more room to reach a good compromise between transmissivity control, visibility and diffraction. In the past the Barco simulation department (now Esterline SVS) has used such blending technic, the Figure 7 shows such example.

![Figure 7: Example of dithered pattern for blend](image)

However, even with the additional degree of freedom in generating the blend pattern, the perfect blend is still not achievable for multiple reasons:
We still have a lot of edges; we can only reduce their impact.
The very bright and very dark areas have no choice but to use a very small pattern.
The visibility of the pattern depends a lot on the exit pupil size which decreased a lot in size since the early days of blending so that the margin between diffraction and pattern visibility is not enough anymore.
It also has the challenge that given its strong dependency on the pupil size, the good parameters can be different for every projector, and even for different zoom levels of the same projector.

On top of this, though the pattern visibility can be anticipated to some extent, the diffraction visibility is far more difficult and does require actual physical testing.

Last but not least, as both the quality of the image and the grey level depends on the shape of the pattern, using dithering requires a marking technology with very high geometric accuracy.
Compared to comb pattern, we can now design complex blend shapes (4 sided), and the additional headroom allows in some cases to have acceptable control on the crossfading to use them even during day scenes.

**Gray scale**
In order to limit the troubles of the dithering it is logical to turn to a grayscale capable technology.
The concept of a technology providing grayscale has no drawback as such, the difficulty arises in finding such a technology which also meets the other requirements of a blend plate (lifetime…)
On the other hand, the geometry accuracy of the dithering is not needed anymore, as there are no small details anymore in the blend pattern.

**Technologies**
**Lasered film**
Lasered film is a common technology having optical characteristics acceptable by design. It also yields very good geometry accuracy and share the cost effectiveness typical of films.
This is however limited to full transparent/full black. It is therefore a very appropriate technology for dithering technics, but obviously suffers from the drawbacks of the films expressed earlier.

**Chromium on glass**
There exist multiple ways of applying chromium on glass. When using dithering, it is possible to manufacture single units of pattern at a reasonable cost.
In this case, we do have the limitations of the dithering, but unlike the lasered film we benefit from the glass substrate. The chromium itself is also a long-lasting marking (equivalent to infinite for our application) so this technology can brag of being the best that dithering can offer.

There exist also manufacturing processes allowing creating gradients with chromium on glass, however such technics involves non-recurring engineering cost for each new pattern making it unaffordable for the low quantities of the simulation market.

**Photographical films**
When one thinks about proper reproduction of grey scales, photography is an immediate domain coming to mind.
As such the use of specific transparent photographic films allows marking a perfect gray-scale pattern.
Unlike the lasered films, photographic films are less used in optical applications. As a consequence such technology first needs engineering and tweaking to have it optimized for our application.
This is a technology on which the Esterline SVS team has gained a lot of experience over the years in order to have perfectly controlled blends on any kind of system.
This is the first technology allowing a perfectly controlled blend, but still with the limitations of the film substrate.
Digital Printing on Glass
After reviewing the first three technologies, the obvious follow up is a technology allowing gray-scale directly on glass. The immediate thought is the use of nowadays direct digital printing to glass.
From a helicopter view this technology seems perfectly fitting, but when looking in details it becomes obvious that standard of the shelf glass printing will not be usable for multiple reasons:
Inks are not designed to sustain the luminous flux of a modern simulation projector
Just like a regular printer, grayscales are actually printed by using thousands of black dots, meaning this is actually a technology using dithering!!
On top of these, as this is digital printing, the accuracy is limited to a certain accuracy, which even if considered very high in the printing industry, is still by orders of magnitude to rough versus light wavelength to print a correct dithered pattern.

So from an ideal technology the deeper look shows this is a useless technology for us in its current state.
However, these challenges just like others can be overcome. In particular Esterline SVS is working on improving this technology to make it suitable for blend plate manufacturing.
For the first issue, Esterline is engineering custom inks to meet lifetime requirements.
Additionally, a custom digital printing flow is being created in order to turn this dithered based technology into a true gray scale technology.
With such technology the ideal blend plate can be manufactured:
- Use of AR coated glass plates yields
  o highest transmissivity which can be expected
  o untouched image for the Main area
- The controlled grayscale gives full control on the blend area
- Proper ink and printing process can yield extinction values in the black area sufficient to be considered as ideal in our application

CONCLUSIONS
After introducing the need for optical blending, most common optical blending technologies have been reviewed, highlighting their strengths and weaknesses.
As none of the current technology meets the ideal specifications, a new being developed technology has been introduced, to finally meet the promises of optical blending.

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