Colour-Managed LED Walls for Virtual Production

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Figure 1: Comparison of a screen-capture from Unreal Engine (lhs) and a frame grabbed from Alexa LF camera (rhs). Images from *Fireworks* ©2021 Wilder Films.

ABSTRACT

We present DNEG's approach to colour-managing LED walls for in-camera VFX in virtual production. By characterising the entire imaging pipeline end-to-end with a closed loop, we enable film-makers and visual effects artists to prepare virtual environments in advance of shooting, confident that their colour intent will be preserved in the final footage. Our system flexibly adapts to the Cinematographer's choice of exposure and white-balance, allowing them to focus more on story-telling and less on technical constraints of the wall.

Our contribution takes place in two stages; first we measure and characterise the response of the camera to the LED wall; and secondly we apply the results of this characterisation in real time to images as they are displayed.

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1 INTRODUCTION

Taking a film crew on location is costly and a complex logistical problem at the best of times. Attempting this amidst a global pandemic is almost impossible, so the possibility of recreating a location virtually on a wall of LED screens has rapidly caught the attention of film makers. To be effective, the final images need to appear as if the camera was really filming the original location, and in this talk we discuss DNEG's approach to colour-managing LED backgrounds for this purpose.

Capturing or creating detailed photo-real content is a staple of most visual effects vendors. A lone operator with an DSLR can easily create a high dynamic range panorama from a single viewpoint, or armed with a drone, can use photogrammetry to create highly detailed, textured scenes. However our informal survey revealed that when displaying this material on LED walls, many companies were treating the wall like a large television, configuring it to display visually-pleasing images, and then laboriously adjusting the colour controls on set to achieve the desired look in camera.

Our approach is to use the movie camera itself as the measuring device. By displaying colours on the LED wall and simultaneously reading the camera's SDI output of these colours, we're able to model, and invert the full imaging pipeline.

2 TECHNOLOGY PROGRESSION

A *process shot*, filming action in front of backdrop image, has a long history dating back to the black and white era. As projection, camera, and computer technology have advanced, so has the technique adapted to take advantage of these improvements.

The current state of the art is to generate photo-real images interactively using game-engine technology, and to display those images on giant LED walls surrounding live action. Low-latency camera tracking matches the in-game camera with a real camera, allowing the virtual environment to be displayed in the correct perspective from the camera's viewpoint.

In *First Man* (2018), DNEG used an early version of the colour calibration system described here. Pre-rendered footage of exterior environments displayed on a $100' \times 34'$, 180° LED wall formed the background to many shots [Kadner 2018]. The upcoming movie *Fireworks* (2021) was shot using the technology in the form presented here.

It's reasonable to assume other productions are using colour management solutions to achieve their results. Unfortunately there's

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no supporting information publicly available at the time of writing to reference or confirm what techniques are being used.

3 GOALS

The overarching goal of this project is to manage the colours on large LED walls in a way that enables a cinematographer to focus on the creative aspects of lighting to support the story. They should not be burning valuable time just matching the colours approved in pre-production. That needs to be the *starting point*. We do this by:

- Preserving colour values through the entire imaging chain.
- Mirroring the controls a cinematographer uses to adjust exposure and white balance.
- Achieving this in real-time and avoiding the introduction of visual artefacts.

By preserving colour, we mean we should be able to take a digital image, display it on a LED wall, film that wall with a digital movie camera, convert that RAW footage back to a digital image, and match it side-by-side with the original. Equivalently, someone should be able to record a high-dynamic-range photograph at a location, display that photograph on the LED wall, film that wall, and have the movie camera respond as-if it had been present in the original location.

Exposure and white-balance are fundamental controls on a movie camera and are adjusted for both technical and creative purposes. Most LED walls have a natural white balance somewhere around 6000K and are limited in their maximum light output by their physical design. As far as possible we don't want these factors to dictate how the cinematographer works. Choice of white balance is typically driven by the practical lights on set, so should the scene include candle-light, for example, the camera will likely be adjusted for a 3200K white and the images on the LED wall will need to sit well in that environment. Similarly the cinematographer may want to adjust the exposure for creative purposes, and we should be able to adjust the wall's luminance to compensate, without introducing any colour shifts.

A guiding principle we use is to only gently modify the signal being set to drive the LED walls; to only use smooth and well-behaved functions and avoid creating visual artefacts such as banding or posterization, as these are far more objectionable and more difficult to fix in the final images than an incorrect colour cast.

4 METHOD

The first stage of our system is characterising the imaging system which currently takes several hours. It is typically done in advance of the shoot day. It comprises three steps: Measurement, Analysis, and Validation.

We measure the response of the imaging system by sampling the space of colours the LED wall can produce. An automated process displays and captures colour patches through the camera using Unreal. We display colour patches through NDisplay and use Unreal's media capture plug-ins to record the camera's SDI feed. Using NDisplay for this step also ensures that we are using the same imaging path as in the subsequent shoot. We generate ~1000 samples and measure them at two different exposures to ensure a good signal-to-noise ratio. We also repeat this process at multiple white-balance settings on the camera.

We model the imaging chain as closed loop where colours present in an image on computer are transmitted to a LED Processor where they undergo a series of transforms, approximated by:

- Linearisation of the high dynamic range transfer function,
- Color space transforms,
- Creative colour adjustments,

before being transmitted to the LED Tiles where Pulse Width Modulators independently drive the three colour LEDs.

The camera records the response of sensors, located behind the lens, under three colour filters before applying its own white balance, colour transforms and logarithmic-like encoding to the resulting image. We invert the camera's logarithmic encoding and transform colours back to our internal working space.

Where possible we concatenate and simplify these transforms with invertible operations. This lets us propagate our colour samples and their subsequent measurements around the loop in either direction, and iteratively improve our estimates for the unknowns in each operation.

The result of this analysis is applied to linear, high dynamic range pixel values in our customised version of Unreal Engine. The operations are implemented as a 3x3 colour matrix, three 1D look-up-tables in addition to the required display encoding function. Any residual errors are partially corrected in a smooth 3D LUT applied as a final stage.

We hold back a random sample of measurements for numerical validation of the process, but have found it's also important to demonstrate the results visually. We do this by simultaneously displaying a set of test images on our workstation monitor, the LED wall, and on the video assist monitor live from the camera. We use a LUT box to reconcile the logarithmic camera signal with the colour output from the workstation. The result is the two monitors showing almost identical images side-by-side.

5 DISCUSSION

Our colour transforms are currently implemented in Unreal Engine, but could be easily converted to other technology, or implemented as an OpenColorIO configuration. Our approach tackles the problem of preserving colour of light viewed directly from the LED wall, but not the problem of using the wall to illuminate coloured objects in the physical set, which is ongoing research.

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