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Illumination Content Player

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Abstract

LED-based tunable luminaires are capable of reproducing with high degree of fidelity a variety of constant and time-varying illuminants. The quality of a particular light source is characterized by color-rendering fidelity metrics (CRI, CIE-51, and more recently, TM-30), which quantify the closeness in appearance of a specific set of color evaluation samples under a test light source and a reference source. We present an approach to optimizing the output of a multi-channel light source for any desired illumination spectra and for any given set of color evaluation samples; discuss examples of useful lighting other than thermal and daylight illuminants and the value of time-changing illumination; and describe the basic operation of illumination player.

A Multi-channel Illumination Source

Constancy of illumination color is one characteristic of a quality light source. A modern luminaire should be capable of maintaining the color coordinates, which is an example of a functionality for which a number of independently addressable LED channels are necessary.

An example is a light source controlled by combined amplitude and pulse width modulation and thus capable of deep dimming. Such a source requires three channels to compensate for the dependence of emission spectrum of an LED on current amplitude, and thus maintain the color coordinates in a wide range of luminous output.

Another example is a temperature-compensated constant correlated color temperature (CCT) module comprising three channels: two over-converted white LEDs with distinct spectra and a direct red LED [1]. This source maintains its color coordinates while the temperature is changing, particularly during the warm-up. Color channel drive levels are tuned to compensate for the temperature-sensitive output of a direct red LED.

In the above two examples the role of independently addressable LED channels is to provide minor tunability so as to keep the color coordinates and light output of the luminaire on target. Now let us consider an emerging class of tunable luminaires that are capable of outputting high-quality white light in a specified range of color temperatures and light output levels.

Tunable White Light Sources

An attractive property of a tunable luminaire is its ability to approximate high quality white light – which is understood as Planckian light or daylight at Earth surface – at any desired CCT within a certain range. “High quality” here refers to accurate control of the color coordinates of the luminaire, and to fidelity of color rendering characterized by metrics like CRI, CIE-51, or TM-30 [2]. These metrics quantify the closeness in appearance of a specific set of color evaluation samples under a test light source and a reference correlated CCT source.

The range of CCT accessible to a source depends on the number of channels and the choice of their emission spectra. Consider, for example, a three-channel system of royal blue, red, and phosphor converted (PC) green LEDs [3]; and compare it to an 8-channel system of 420nm violet, 450nm royal blue, 475nm blue, 500nm cyan, PC-lime, PC-amber, 630nm red, and 660nm red LEDs. This three-channel source is capable of approximating thermal radiation in a narrow range of CCT around 2800K, with CRI R_a of 92. In comparison, the range of CCT accessible to the 8-channel source is from 1200K to above 50,000K, with excellent color rendering (CRI $R_a > 98$) for CCT above 1800K.

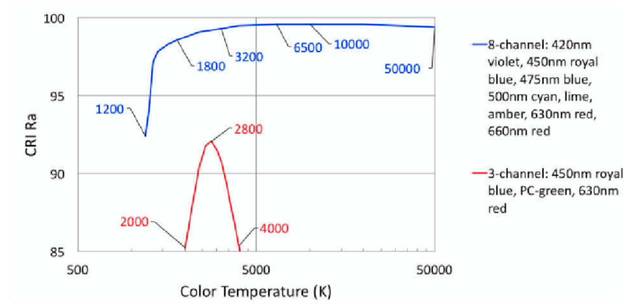

Figure 1. The range of accessible color temperature vs. number of independently controllable channels

It is important to note that the gamut defined by three channels may be wide enough to cover a large segment of Planckian or daylight locus. Such a system is capable of generating on-Planckian light in a wide range of CCT, but due to its limited spectral content, this system will have poor color rendering everywhere except possibly in a narrow part of the CCT range, and thus will not be suitable for tunable illumination.

Beyond Daylight

Having demonstrated that tunability of white light output of a luminaire is related to the number of independently controllable channels, let us recall that color coordinates and luminous output do not uniquely define the spectra of systems having more than three independently controllable channels.

Consider an RGB display used as a flashlight approximating illuminant D65, for example. The target expressed by the intensity of the flashlight and the color coordinates corresponding to D65 source constrains intensities of R, G, and B pixels of the display to three unique values. In other words, there is a one-to-one correspondence between the target and the illumination spectrum of the display, so long as the color coordinates is chosen within the available gamut and the intensity of the display is within the attainable range.

With N independently controllable channels ($N > 3$), three constraints imposed by the target color coordinates and luminous output, leave us with $N - 3$ degrees of freedom, and thus many possible linear combinations of channel spectra will satisfy these constraints. The number of combinations is limited by bit resolution of the luminaire. An array of N-channel luminaires

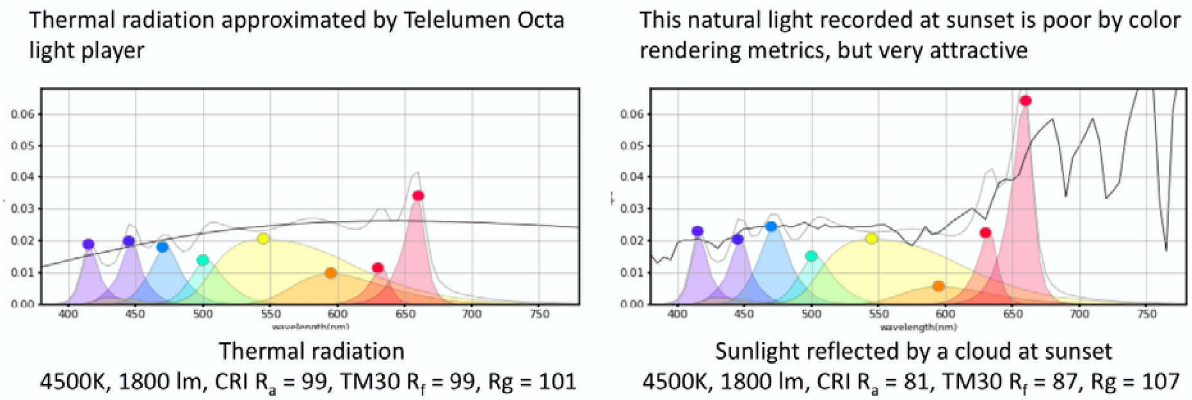

Figure 2. Thermal radiation and recorded natural light approximated by an 8-channel luminaire

having the same color coordinates and luminous output but emitting different spectra will appear the same when looked at directly, but will render object colors differently. Other properties related to human perception, for example, circadian phase response, will also be different.

While a multichannel illumination source can be used to approximate standard white light illuminants with high fidelity, its unique advantage lies in the possibility of synthesizing other useful illumination spectra, for example, those naturally occurring, not easily observable, or appearance-enhancing. This can be best explained by considering an example luminaire, an 8-channel source, first configured to approximate Planckian radiation at 4500K, then configured to approximate recorded spectrum of sunlight reflected by a cloud at sunset, at the same CCT, below Planckian locus ($d_{uv} = -0.011$). These two configurations are shown in the figure above.

The approximation of thermal radiation in the figure above is accurate by all relevant metrics (R_a = 99, TM30 R_f = 99, R_g = 101). The natural light recorded at sunset is also accurately reproduced by the luminaire in terms of CIE $L^*a^*b^*$ distance ΔE_{RMS} between a set of test color samples illuminated by the recorded light and by the luminaire. By conventional color rendering metrics, this light is rather poor (R_a = 81, TM30 R_f = 87, R_g = 107). It is, however, a very attractive light, as we all know from observing nature at sunset: the colors of objects are warm, and human skin is more vivid.

Content Players

A great variety of illumination spectra can be synthesized for various purposes by multichannel light sources [5]. The most obvious use case is accurate approximation of daylight in a wide CCT range, as discussed above. Spectra may be engineered to alter color rendering in order to make objects look more appealing [6]. UV (and violet) channels may be added to a luminaire in order to accurately render colors of fluorescent materials, for example, fabrics with added optical brightening agents [7]. Near-UV, far red and IR channels may be added to make the source suitable for plant growth, configurable for different plants and growth stages [8].

When time dependence of illumination is added, a multichannel light source becomes an *illumination content player*, sequentially outputting spectra by driving channels according to channel output levels defined in *lumenscript* files [9]. We will call the output spectra *frames*, by analogy to a video recording. The lumenscript files encode dynamic lighting, such as a full day of sunlight at a given latitude and time of day, candle light, fire, light modified by passing clouds, light under tree canopy, Aurora Borealis (Northern lights), and so on.

A network of luminaires may synchronously play different lumenscripts. For example, an array of luminaires may be installed in the ceiling, forming a low-resolution illumination display. A light recording of the partially cloudy sky at sunrise done by a multispectral camera can be mapped to this array of luminaires, recreating the rich illumination effect of the sky.

A high-level schematic of a possible implementation of an illumination content player is given in the next figure [[5], [10]].

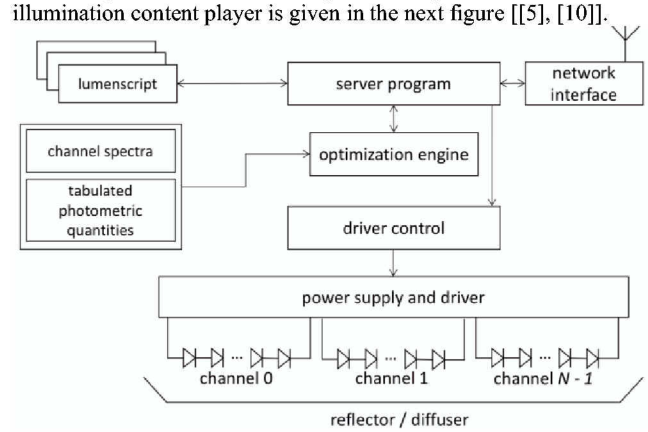

Figure 3. A high-level schematic of an illumination content player

The player stores in its memory a playlist of lumenscripts compiled by the optimization engine from timed sequences of target spectra, based on relevant photometric data and luminaire characteristics. The latter typically are representations of channel spectra for an array of drive levels and temperatures. Timed sequences of target spectra from which lumenscripts are compiled are sent to a luminaire over the network interface. The server program commands the driver control to play a specific lumenscript in response to a user action or according to a specified schedule.

To further illustrate the concept of illumination player, we consider a short lumenscript: the emulation of power-up of an incandescent / halogen lamp that mimics house lights coming up in a theater rather than lights turning on at a flip of a switch). Telelumen 8-channel Octa luminaires play this lumenscript when turned on, starting at a very low light output (several lumens) and the lowest CCT accessible to this luminaire (1150K), and ending at a moderately high light output (2000 lm) at 3000 K. Compression of incandescent light output range is necessary, since the dynamic range of a high-end commercial grade luminaire is typically limited to 3 or 4 orders of magnitude. In the figure below, several frames from the power-up lumenscript compiled for an 8-channel luminaire are shown in the next figure.

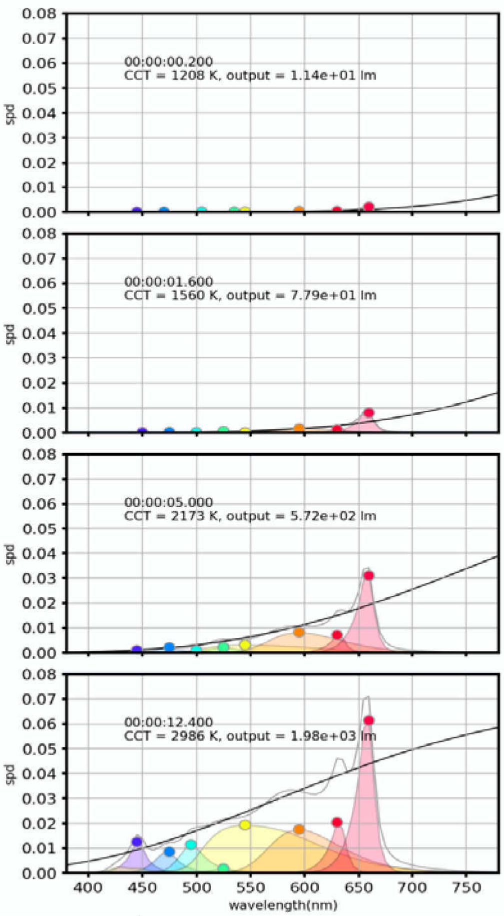

Figure 4. Frames from the incandescent bulb power-up lumenscript compiled for an 8-channel luminaire

The light played by the illumination player may also be visualized in a way similar to a spectrogram of an audio recording. The progression of frames during the power-up of an incandescent bulb is shown below as a heat map (blue is low spectral power, red is high). Spectra are represented by columns, rows correspond to individual frames.

The overall change of CCT is from 1150 K to 3000 K, and the corresponding change of output is from 2 lm to 2000 lm, occurring over several seconds. Accurate synthesis of light in a wide range of lumen output is therefore important for creating a realistic effect of incandescent bulb power-up.

We demonstrated yet another advantage of multichannel light sources: the warm range of color temperatures down to 1150K would not have been accessible to a typical RGB source.

This example helps us formulate typical properties of a light player:

- The player should have 8 color channels or more, including phosphor-converted channels, the latter necessary for color rendering and efficiency. In order to attain a wide range of CCTs where light can be optimized for high color rendering we select six direct LEDs with peak wavelengths from 420nm to 660nm, and two phosphor-converted LEDs, a total of 8 channels
- Violet and/or UV channels should be included for accurate rendering of fluorescent samples
- Dynamic range of accurate approximation of desired spectra should be at least 30 dB (1000:1)
- Update rate of illumination spectra should be at least 1000 fps
- Dynamic range of channel output level should exceed 1000: 1 by at least an order of magnitude for accurate approximation of light with 30 dB dynamic range; 16-bit channel resolution is adequate.
- No perceivable flicker is allowed; this can be achieved if minimum duration of a frame is short (about 1ms)
- Transitions between frames should be smooth

Color evaluation samples

The role of optimization engine is to compute the array of output levels of *N* channels that best approximates the target spectral power distribution (SPD). The best approximation is not necessarily the one for which the RMS difference between the target and synthesized spectra is minimized. In the case of a limited number of channels an arbitrary shape of target SPD is unlikely to be approximated by a luminaire with high accuracy. An optimization goal more relevant to human vision is minimization of the difference in appearance of test color samples from a certain *palette* under target light and synthesized light [[11]]. With a large number of independently controllable channels these two optimization goals converge: if a luminaire is capable of accurately approximating the target SPD, all photometric properties will fall into place.

The palette used by the optimization engine may be selected from a tabulated set of color evaluation samples (CES), such as CRI, CQS [[12]], CIE-51 [[13]], TM-30, Munsell colors chips, or any commercial set of colors, or a concise mathematical representation of a large set of colors.

Color vector: a relevant representation of an SPD

As discussed above, the optimization engine compiles target spectra to channel output levels maximizing the closeness of appearance of a CES palette under the target light and the light emitted by a luminaire. Any given SPD, therefore, can be represented by a *color vector*, which is an array of tristimulus values of light having this SPD reflected by *P* samples of the palette – although there may be more general definitions. The color vector can be calculated as follows.

Spectrum reflected by a color evaluation sample p is expressed as $\boldsymbol{S}_p(\lambda) = \boldsymbol{S}(\lambda) * \boldsymbol{R}_p(\lambda) + \left(\boldsymbol{Q}_p(\lambda) \cdot \left(\boldsymbol{S}(\lambda) * \boldsymbol{k}(\lambda)\right)\right) \boldsymbol{F}(\lambda)$. The first term is me an element-by-element product

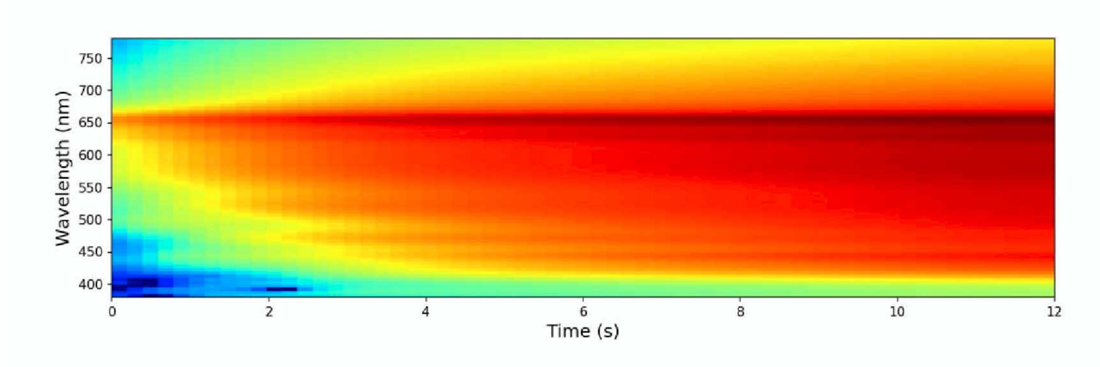

Figure 5. Power-up of an incandescent bulb approximated by an 8-channel luminaire shown as a heat map of spectral power distribution vs. time

of spectrum of incident light $\boldsymbol{S}(\lambda)$ andthe reflectance spectrum of sample $p,\boldsymbol{R}_p(\lambda)$. The second term accounts for possible fluorescence of the sample. SPD of incident light $\boldsymbol{S}(\lambda)$is multiplied by function $\boldsymbol{k}(\lambda)$that converts it from power units to photon flux units. Wavelength-dependent quantum yield spectrum$\boldsymbol{Q}_p(\lambda)$is the ratio of photons absorbed and reemitted to incident photons, and $\boldsymbol{F}(\lambda)$ is the spectral power distribution of fluorescence per unit of photon flux. If sample p is not fluorescing, the expression is reduced to: $\boldsymbol{S}_p(\lambda) = \boldsymbol{S}(\lambda) * \boldsymbol{R}_p(\lambda)$.

For each color sample, we can calculate tristimulus values of $\boldsymbol{S}_p(\lambda)$, the spectrum of light modified by sample p, as scalar products of $\boldsymbol{S}_p(\lambda)$ with color-matching functions: $X_p = \boldsymbol{S}_p(\lambda) \cdot \overline{\boldsymbol{x}}(\lambda)$, $Y_p = \boldsymbol{S}_p(\lambda) \cdot \overline{\boldsymbol{y}}(\lambda)$, $Z_p = \boldsymbol{S}_p(\lambda) \cdot \overline{\boldsymbol{z}}(\lambda)$

Color vector corresponding to incident spectrum $\boldsymbol{S}(\lambda)$ is therefore equal to

$$\boldsymbol{c} = [X_0, Y_0, \quad Z_0, X_1, Y_1, \quad Z_1, X_{P-1}, Y_{P-1}, \quad Z_{P-1}]$$

Luminaire color array

SPDs of a luminaire having N channels can be converted to N color vectors $\boldsymbol{c}_n$, each normalized to the output of 1 lumen (or 1 lux, or any other relevant integral photometric of the output). The linear combination color vector of a luminaire is expressed as$\boldsymbol{c} = \sum_{n=0}^{N-1} l_n \boldsymbol{c}_n$ where $l_n$is luminous outputs of the n-th channel. Normalized color vector $\boldsymbol{c}_n$ may be independent of the drive level, which is typically the case for PWM control, but is not the case for combined PWM/AM control, since spectral shapes of LEDs depend on forward current amplitudes. A more accurate expression of the luminaire color vector will thus include the (typically weak) dependence of $\boldsymbol{c}_n$on $l_n$as follows: $\boldsymbol{c} = \sum_{n=0}^{N-1} l_n \boldsymbol{c}_n(l_n)$. Drive-level dependent channel color vectors$\boldsymbol{c}_n(l_n)$ can be interpolated from measurements of each channel at M drive levels spanning the range of 0.1% to 100%, for example. These measurements are stored as a luminaire color array of size$N \times M \times V$array (N channels, M drive levels, V color vector elements).If normalized channel color vectors are independent of drive levels, the luminaire color array is a two-dimensional array of size $N \times V$.

Optimization

The optimization cost function $f(\boldsymbol{l})$ is a function of channel output level vector $\boldsymbol{l} = (l_0, l_1 \dots l_{N-1})$. Based on the arguments above, it can be defined as the RMS error of palette appearance under the target light and the approximated light, which is the square of the difference between target color vector and the color vector of the luminaire:

$$f(\boldsymbol{l}) = (\boldsymbol{c}_t - \boldsymbol{c}) \cdot (\boldsymbol{c}_t - \boldsymbol{c})^T, \text{ where } \boldsymbol{c} = \sum_{n=0}^{N-1} l_n \boldsymbol{c}_n(l_n).$$

The optimization engine minimizes cost function $f(\boldsymbol{l})$ under the following inequality constraints:

(1) $0 \le l_n \le l_n^{\max}$ where $n = 0 \dots N-1$ and $l_n^{\max}, n = 0 \dots N-1$ is the maximum luminous output level of the n-th channel

and the following equality constraint:

(2) $\boldsymbol{T}_t = \sum_{n=0}^{N-1} l_n \boldsymbol{t}_n(l_n)$, where $\boldsymbol{T}_t$ is the vector of three tristimulus values of the target spectrum, and $\boldsymbol{t}_n(l_n)$ is avector of tristimulus values of channel n at output level l_n , normalized to the output of 1 photometric unit.

The first set of constraints asserts that channel luminous outputs are within physically attainable range. The second set of constraints is an expression of the requirement that the target light and the approximation must appear identical to an eye when looked at directly. It is easy to see why this constraint is important, especially when a number of proximal luminaires are all reproducing the same target spectrum: if this constraint is not satisfied, any difference in intensity or color among closely positioned luminaires will be immediately obvious. The optimization process executed for all (possibly dissimilar) luminaires ensures that the differences in color rendering of the chosen CES palette are as small as possible.

Some channels may be set to a fixed value of output, which creates additional constraints on optimization. For a luminaire array configured to play a single sequence of targets, the computational load of compilation to lumenscripts depends on the dissimilarity of the luminaires. For example, if all luminaires are of the same type and are built with closely binned LEDs, only one run of optimization per target SPD sequence will be required, generating an identical lumenscript for all luminaires in the array.

Finally, we point out that our approach is not limited to approximating color rendering properties of target illumination. Consider this optimization problem for a source that contains both visible and IR channels instead: the goal is to maximize photosynthetically active radiation (PAR) value of the illumination, for a given luminous output and the color coordinates.

In conclusion, we believe that we demonstrated that LED-based tunable luminaires will become ubiquitous in the near future thanks to their attractive properties: high quality of light in a wide range of color temperature, accurate synthesis of special-purpose illumination different from white light, and the ability to play sequences of light spectra reproducing varying illumination.

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