Color Management for Digital Video: Color Correction in the Editing Phase

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ABSTRACT

In this paper we describe the preliminary results of a collaborative research project conducted by researchers at Gjøvik University College and Lillehammer University College. The goal of the project is to develop methods and tools to improve the control of color information in the production and presentation of digital video. The project represents a unique attempt to bring together two scientific communities — graphic arts and television/video production — on a theme of common interest, namely color. Promising results have been obtained by using an innovative color warping algorithm for color correction in editing of digital video.

1. INTRODUCTION

Ever since the beginning of the color film era, color adjustment has been a permanent area of difficulties in the production of moving pictures (Roderick, 1976). The use of several cameras simultaneously or at different times and under varying lighting conditions, results in varying color rendering in the different captured shots. When these shots are edited together, the colors must be harmonized, and this requires substantial manual adjustments. The fact that shots are often taken under lighting conditions which are different from the those desired to tell the story, has also led to extensive color corrections by use of color filters and laboratory chemicals.

The introduction of video technologies changed the methods of work, but color corrections remained a tedious process, requiring expensive equipment for use in professional environments. The transition from analog to digital video now opens the possibilities for developing methods of video color management, by applying principles similar to those already in use for digital image reproduction on various media. Digital video color management can potentially be implemented using common computer platforms, and equipment which cost a fraction of today's dedicated video editing and color correction equipment. At the same time, the processes can be simplified and made less time-consuming. Such solutions will have the potential of strengthening smaller production environments with limited resources and increasing the possibilities for distributed production of video material.

In a collaborative research project involving researchers from the neighboring institutions Gjøvik University College (GUC) and Lillehammer University College (LUC), it was decided to investigate further into this interdisciplinary area of research and development. The research project was funded by Morgenlandet AS, a regionally based company which aims for restructuring and innovation, and has a duration of two years (2002-2003). It brings together two scientific communities — color science and color management mainly for graphic arts applications at GUC, and video, television, and film production at LUC.

In a recent interview, Garrett Smith of Paramount Pictures states, when discussing the problems with varying aspect ratio in digital television: "Please be careful before you trespass on the visual integrity of these motion pictures" (Fisher, 1999). This quote can serve as a motivation for the present study. Whether the film-maker's goal is to convey realism — a sense of 'being there' — to invoke certain emotions, or to use the diverse symbolic meanings of color, color is a very important part of the visual integrity of motion pictures (Jørholt, 1998a;b). Our overall goal is to make sure that the creative use of color in the production of all types of moving pictures is not compromised because of technological limitations. Obviously, a great deal of what it would take to achieve this lies completely out of our reach, so we decided to limit our scope to digital video. This is partly because of the obvious flexibility inherent to digital video processing using today's powerful computers, but also because digital video technology is now very quickly replacing traditional film technology for many applications. This is particularly true for amateur video production and

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digital broadcast television, but also the concept of *digital cinema* is now being introduced (Manovich, 2001, Korris and Macedonia, 2002).

We have identified four different research topics of particular interest (Andresen *et al.*, 2001):

1. Color management in the acquisition of digital video. This topic includes problems such as automatic white balance, colorimetric characterization of cameras, and the use of color targets in the acquisition process.

2. Color control for editing of digital video. Here we pay specific attention to the tasks typically performed by a colorist – adjusting colors of video sequences in order to obtain certain effects/moods, and also to match the colors of other sequences.

3. Color characterization of monitors used in the production of digital video. Here we investigate how color management principles, typically ICC-based, can be applied to a video production environment in which several different monitors are used simultaneously.

4. Color quality of projective displays used for presentation of digital video. The use of digital projective displays for the presentation of moving pictures is growing rapidly, both in a home theater environment, and in public movie theaters. However, very little scientific work has been published on the colorimetric characterization of such displays, and on the resulting color quality. Does the quality match conventional cinema technology? Does the presented colors appear the way the producer intended them? We address these questions both through visual assessments and by using advanced measurement instruments such as a spectroradiometer.

In sum, our overall approach to color management in digital video is to strive for consistent, repeatable, and automatic processing of color information in all parts of the production and presentation chain, except in the editing phase, where creativity is desired.

The rest of this paper is organized as follows: In Section 2 we introduce several aspects of color management for digital video, and in Section 3 we propose our approach to the problem of color correction in editing of digital video. Finally, in Section 4 we draw some conclusions and directions for further research.

2. COLOR MANAGEMENT FOR DIGITAL VIDEO

Recently there has been a significant proliferation of digital equipment in several branches of imaging technology — still photography, video, cinema, printing and publishing, medical imaging, to mention a few. This has resulted in a convergence in media technology — the technological differences between different imaging technology branches are disappearing, at least when described at a certain conceptual level. In light of this it is a logical proposition to investigate whether sciences and practices that has been used in one branch can be applied successfully to another branch. In particular, in this section, we present several ways in which color management principles and techniques can be used in production and presentation of digital video. We begin with a short literature review on the subject and a brief introduction to the principles of color management. Then we present the basics of colorimetric characterization of displays, followed by the concept of soft-proofing of video displays. Finally, we present a new approach to determining the relationship between two color spaces by using a geometric warping technique.

2.1. Prior art

The use of digital color management for digital video and motion pictures has not been much studied in the past, but we have found a few recent references. Anders Kraushaar of FOGRA Germany has described the implementation of an ICC-based Color Management System within the post production scenario in the motion picture industry (Kraushaar, 2002, Kraushaar and Gall, 2002). Their main aim was to improve the predictability of color by soft-proofing the cinema screen on Class 1 video studio monitors. They have reported significant improvements in terms of ΔE color differences, but states that improvements are still needed for some special color regions.

Ramamurthy *et al.* (1999) describe the development and implementation of a ICC-compliant color management system in the production environment of a major feature animation studio, with the goal of achieving color match between scanner, monitor and film. They report that in the production of the film *The Iron Giant*, significant savings in time, material, and labor was achieved due to the use of color management. However, they also point out several problem areas, such as varying viewing conditions, stability of devices, and profiling of negative film.

Benedikt *et al.* (1998) explores the possibilities of using a test target with color patches placed in the scene to be captured, thereby establishing a link between the captured video and the original scene.

Noriega *et al.* (2001a;b) propose an algorithm for colorimetric characterization of a cinema film scanner, including the difficult task of dealing with negative films. Lempp and Noriega (2002) discuss the different challenges for development of a color-managed digital film post-production process chain.

2.2. What is color management?

Digital color imaging systems process electronic information from various sources; images may come from the Internet, a remote sensing device, a digital camera, a desktop scanner, etc. Employing the ever increasing available computing power, a vast variety of image processing algorithms might be applied to the images. Examples of such algorithms include image compression, object recognition, segmentation, sharpening, and noise reduction. After processing, an image may be transmitted to one or several destinations via a computer network for further processing and rendering on a computer monitor or a printer (Figure 1).

The different image I/O devices generally process color information differently, for example if you scan the same photo with two different desktop scanners, you will get different digital images, or if you print a digital image on two different printer, the colors of the resulting prints will be different. Using more scientific terms: every imaging device quantifies color information using its own *device-dependent color space*.

To achieve color consistency throughout such a widely distributed system, it is necessary to understand and control the way in which the different devices in the entire color imaging chain treat colors. This can be achieved by performing colorimetric characterizations of the color image acquisition and reproduction devices so that the *device-dependent* color spaces of the scanner, the monitor, the printer, and other color imaging devices, can be linked to a *device-independent* color space, see Figure 2. In an imaging system with N color image input devices and M color image output devices the number of required color conversion paths is thereby reduced from NM to $N + M$. This is the basic principle of *color management*. For more information about color management, refer for example to the books by Giorgianni and Madden (1997) and Green and MacDonald (2002).

The International Color Consortium (ICC) was established in 1993 by eight industry vendors for the purpose of creating, promoting and encouraging the standardization and evolution of an open, vendor-neutral, cross-platform Color Management System (CMS) architecture and components. Its standard for color management (ICC.1:2001-12, 2001) has today wide acceptance, even if some issues still are unsolved.

Several vendors offer CMS software solutions, *e.g.* Microsoft, Apple, Kodak, and Agfa, and it has been concluded (Schläpfer *et al.*, 1998) that the color management solutions offered by different vendors are approximately equal, and that color management has passed the breakthrough phase and can be considered a valid and useful tool in image reproduction. On the other hand, Sharma and Fleming (2002) show that there are indeed quality differences between different CMS vendors.

2.3. Display characterization

Colorimetric characterization of various types of visual display units plays a central role for the implementation of color management in a digital video context. Simply put, the aim of a display characterization is to investigate which colors are actually produced, for given RGB drive signals. This can be measured by use of equipment such as colorimeters, spectrophotometers, and spectroradiometers. Typically, the reproduced color is measured for a few RGB values, and the reproduction for other RGB values is predicted by a display model. By inverting the model, an even more interesting problem can be solved: which RGB drive signal should be used in order to produce a given color?

Two important types of displays are Cathode-Ray Tubes (CRT) and Liquid Crystal Displays (LCD). CRTs can be characterized almost completely in terms of a few parameters — the chromaticities of the primary colors and the white point, the dark level, and the gamma value. When these parameters are known, the required RGB drive signals needed to produce a given XYZ color stimulus can be calculated (Berns *et al.*, 1993, Kang, 1997, Berns and Katoh, 2002). LCDs, however, require more complex characterization models, typically using LUTs (Cazes *et al.*, 1999, Kwak and MacDonald, 2001).

Characterizing projection displays also presents some particular challenges, such as high dark level, chromaticity changes of the primary colors with varying intensity, and poor spatial uniformity (Seime and Hardeberg, 2002).

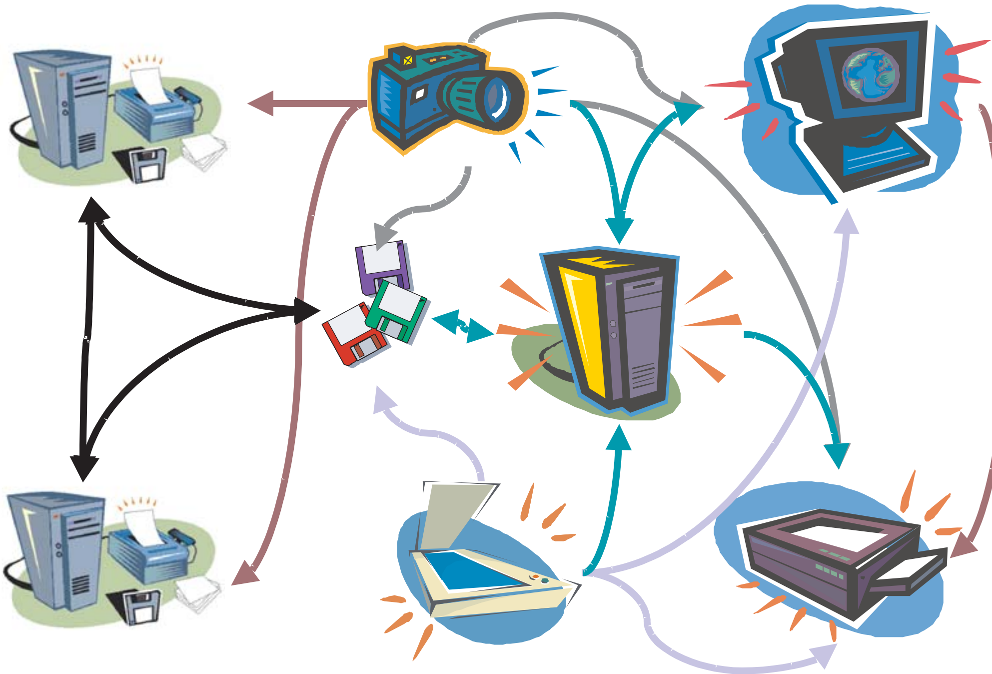

Figure 1. Today's color imaging systems are typically very complex. How can we achieve consistent communication of color?

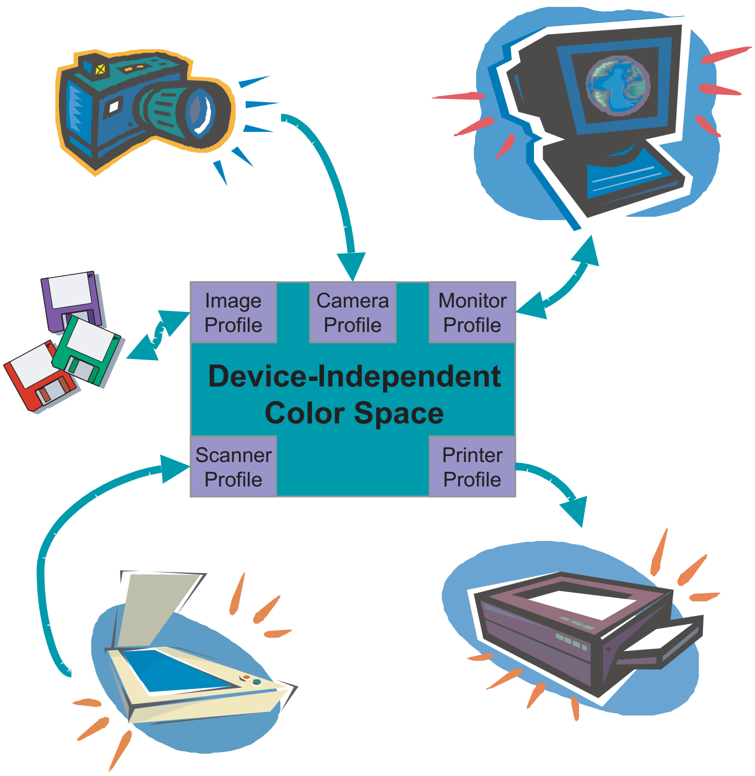

Figure 2. The principle of Color Management. Each imaging device is characterized by a profile. Color information is communicated using a Device-Independent Color Space.

2.4. Color warping algorithm for color space matching

For many color imaging applications it is desired to find the relationship between two color spaces, where no analytical transformation is known, but where the transformation has been determined experimentally at several sampling points in color space. Two applications relevant to this paper is display characterization, where we seek the relationship between the RGB display drive values and a device-independent color space such as CIELAB, and color adjustment in video editing, where footage from different video sources with unknown colorimetric properties are to be edited together, and hence need to be converted into a common color space.

A multitude of algorithms has been proposed for such applications. The most common approaches use either polynomial regression algorithms (Berns, 1993, Lenz and Lenz, 1996, Kang, 1997, Hardeberg, 2000; 2001) or multi-linear interpolation (Kanamori *et al.*, 1990, Hung, 1993, Balasubramanian, 1994, Hardeberg and Schmitt, 1997, Hardeberg, 2001).

We propose here to use an algorithm which we call color warping. Image warping is a technique known from the image processing literature (Arad *et al.*, 1994, Ruprecht and Muller, 1995, Gomes *et al.*, 1999) in which an image is geometrically deformed. Goals for applying this deformation include creating visual effects such as changes in facial expressions, or as a building block for image morphing algorithms in which an image is smoothly and gradually modified into another image in a video sequence. (For an example of image morphing, see `http://www.colorado-research.com/~gourlay/software/Graphics/Xmorph/`.)

While the image warping algorithm is based on a set of source/destination pixel locations in the image plane, our color warping algorithm is based on a set of source/destination points in a given color space. This set of color pairs define the warping of the color space, according to the following properties:

- The source color is directly mapped to the destination color.
- Colors close to a given source color end up close to the corresponding destination color.
- Colors that have the same distance to two source colors are influenced equally by the two source/destination pairs.
- Colors are influenced more by closer source colors.

The warping algorithm can be described more precisely as follows. Given N source color values $\mathbf{C}_S(k)$, $k = 0, 1, \ldots, N-1$, in a given color space, with their corresponding destination color values $\mathbf{C}_D(k)$, $k = 0, 1, \ldots, N-1$, the change of a color is calculated as the weighted sum of the contribution of all source and destination pairs. That is, for a given input color $\mathbf{C}_I$, the warped output color is defined as

$$\mathbf{C}_O = \mathbf{C}_I + \sum_{k=0}^{N-1} w_1(k) w_2(k) \left(\mathbf{C}_D(k) - \mathbf{C}_S(k)\right), \tag{1}$$

where $d(k) = \|\mathbf{C}_I - \mathbf{C}_S(k)\|$ is the Euclidian distance between the input color and the kth source color. The first weight function, $w_1(k)$, is calculated as a normalized inverse distance between the input color and the kth source color,

$$w_1(k) = \begin{cases} \dfrac{1/d(k)}{\sum_{n=0}^{N-1} 1/d(n)}, & \text{if} \min d(k) > 0, \\ \delta(k, k_{\min}), & \text{if} \min d(k) = 0, \end{cases} \tag{2}$$

where $k_{\min} = \arg\min d(k)$ and $\delta(k, k_{\min})$ is the Kronecker delta function which takes the value of one where $k = k_{\min}$ and zero elsewhere. The second weight function, $w_2(k)$, is an exponential function of the distance,

$$w_2(k) = e^{\frac{-d^2(k)}{2\sigma^2}}, \tag{3}$$

corresponding to a normal distribution with a standard deviation of σ. This weight function is introduced in order to reduce the influence of the warping algorithm for colors distant from the source colors.

Note that the behavior of this color warping algorithm depends very much on the color space in which it is performed. In particular, if it is performed in the CIELAB color space, the distance would correspond to the colorimetric color difference ΔE^*_{ab}.

To illustrate the behavior of the proposed warping algorithm, we show in Figure 3 the combined weight functions for an example warping defined in two dimensions by the following source/destination points: $\mathbf{C}_S(0) = (27, 27)$, $\mathbf{C}_D(0) = (27, 126)$, $\mathbf{C}_S(1) = (126, 126)$, $\mathbf{C}_D(1) = (140, 100)$, $\mathbf{C}_S(2) = (126, 153)$, $\mathbf{C}_D(2) = (234, 180)$, and a standard deviation of $\sigma = 50$. We note that the weights are unity in the associated source color point, and zero in the points corresponding to the other source points. The resulting warping algorithm is illustrated by a deformation of a regular grid shown in Figure 4.

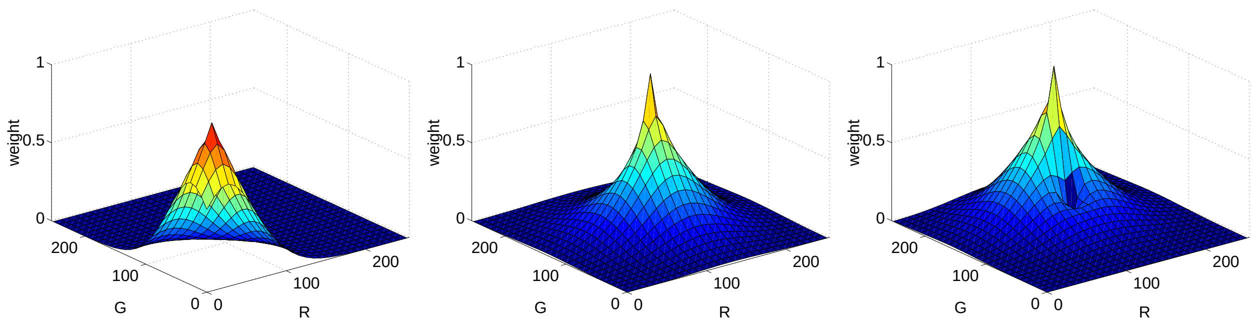

Figure 3. Weight functions for the three source colors and a standard deviation of $\sigma = 50$.

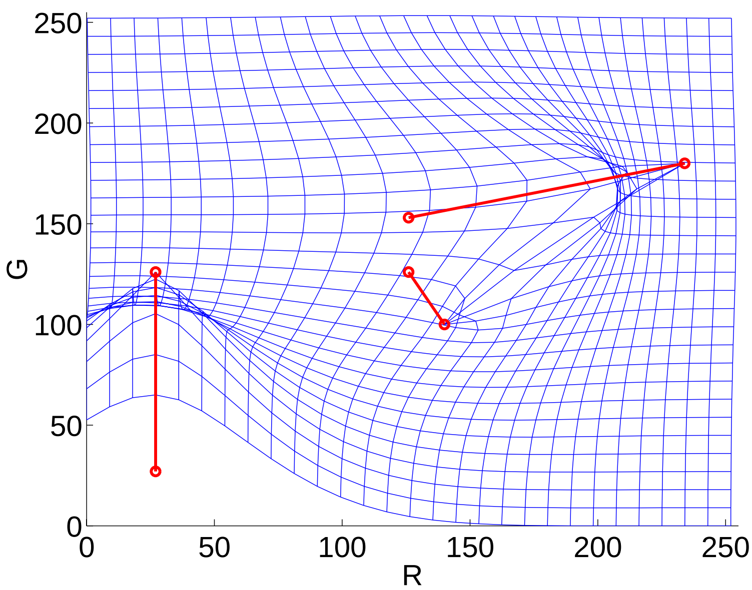

Figure 4. 2D illustration of the resulting deformation using the proposed warping algorithm with three color pairs and a standard deviation of $\sigma = 50$.

The idea of using a geometric warping algorithm for color characterization applications is not a new one. Morovic and Luo (1996) applied a distance weighted interpolation technique for characterizing desktop colors printers without full control over all parameters. A similar approach, replacing the Euclidian distance with the Mahalanobis distance in the weight functions in order to reduce the effects of perceptually inhomogeneities in the color space was used by Noriega *et al.* (2001a;b) for color characterization of a digital cine film scanner operating on negative films. (Spaulding *et al.*, 1995) applied a warping algorithm utilizing point, line, surface, and volume constraints for gamut mapping for several models of Kodak printers in order to obtain a seamless combination of colorimetric mapping for colors with low saturation levels and a color enhancement technique for colors with high saturation levels. A somewhat related study by Balasubramanian and Maltz (1996) used weighted linear lest-squares regression to improve the accuracy of an already existing printer transform using a relatively small number of measurements.

3. COLOR CORRECTION IN EDITING OF DIGITAL VIDEO

In this section we propose our approach to the problem of color correction in editing of digital video. First, we present some previous solutions, then our proposed method, its implementation, and a discussion of the results we have obtained.

3.1. Previous solutions

Several software-based solutions has been proposed for adjusting colors in digital images and video, some can be characterized as manual corrections, some are semi-automatic, and yet some are completely automatic.

Most image manipulation and video editing suites have interfaces for manual adjustment of color balance, brightness, contrast and the like. The brightness and contrast tools are most often adequate and simple to use, while the tools available for color balance are often nonintuitive.

Many users use the Curves tool in for instance Adobe Photoshop to adjust the color balance. The Curves tool is an advanced tool and the result of a user's actions is not immediately obvious. This approach also lacks in that it operates separately on the R, G, and B color channels; you cannot for instance redirect the contribution from the green component to the red component.

The standard distribution of the GIMP (`http://www.gimp.org`) provides more color-correction tools than Photoshop. Even so, only one tool reaches a comfortable level of intuitiveness: the Filterpack plug-in for Gimp provides a user interface similar to a color darkroom. But it does not allow for fine tuning and also depends on user knowledge from other domains.

Film and television studios often use expensive dedicated systems to solve problems of color correction; one of these being Da-Vinci 8:8:8 Renaissance (`http://www.davsys.com`). This system operates in the YC_bC_r color space with individual rollerball controls for the adjustments of the black point, white point and gray point positions. Thumb wheels let the user set the black level, white level, gamma, and saturation.

With relation to semi-automatic color correction not many sources of information were found. The most closely related field of research is color management with color profiles. This approach is easily applied to printed media where almost all variables can be controlled and the image sources are known, but might be less feasible in a digital video editing environment, where the video sources are often of unknown colorimetric properties.

Automatic color correction is already done during image acquisition for most video cameras and digital still cameras. The cameras adjust the white balance and exposure according to the captured data. The ideas and algorithms from this area of color imaging science are useful and can be applied to secondary corrections as well. However, the automatic correction applied by these devices also gives rise to some of the problems that must be amended; different shots of the same scene from different angles often reproduce different colors due to the automatic white balance and exposure.

3.2. Proposed method

Our proposed method can be categorized as a semi-automatic one. When two shots are to be color-matched to each other, the user selects a few corresponding colors in the two shots, typically by using a ”color picker” tool. One clip is considered the reference, and the other is supposed to be adjusted so that the colors match those in the reference. Based on the *source colors* selected from the clip to be adjusted, and the *destination colors* selected from the reference clip, we use the color warp algorithm presented in Section 2.4 to define the desired correction.

In fact, if we approach this problem in a color management framework, the two clips have their own proprietary color space, and our task is to find the transformation from the source color space to the destination color space. This is very much analogous to performing a colorimetric device characterization.

Using the proposed algorithm has several advantages over for example using a linear interpolation or triangulation approach to relate the two color spaces. First, at least four distinct colors would be necessary for a full transformation, for example red, green, blue and white. Finding distinct color pairs distributed in the whole color space would be difficult for most kinds of footage. If perceptually close colors were used, extrapolation techniques would be needed for colors outside of the gamut implicitly defined by the color samples, and small errors would be amplified in the correction.

In a slightly different approach we also wanted to test what could be done if a color target were included in the video sequences, typically in the first few frames of each shot, or each time the lighting condition changes. Based on the colors of the target in the different shots, the shots can be corrected accordingly. It is clear that requiring that a color target be present in the footage presents quite serious limitations to the practical applicability of this approach, but we still wanted to investigate what could be done in the presence of such reference color data.

Regarding the color target, a natural choice would be to use the Macbeth ColorChecker (McCamy *et al.*, 1976) (now marketed by GretagMacbeth as the Munsell Checker Chart), but due to availability problems we decided to make a dedicated target ourselves (Figure 5). While other algorithms for finding the relationship between color spaces based on measured data could probably have been used, we decided to base our work on the already described color warping algorithm.

Figure 5. The test target used, with NCS number for the colors.

3.3. Implementation

We have implemented the warping algorithm in an R&D framework application, see Figure 6. In addition to the warping algorithm, with a graphic user interface including a color picker tool, it also features visualizations of chromaticity diagrams and histograms, manual color corrections by picking white and black point in the image, by moving the image cloud in the chromaticity diagram, etc., as well as standard automatic correction algorithms such as the gray world assumption (Buchsbaum, 1980).

We have also implemented it as a plug-in for Adobe After Effects 5.5, see Figure 7. Adobe After Effects is a nonlinear video editing application for Windows and Macintosh, it provides advanced video cutting and composition tools. The plug-in was developed under Microsoft Visual C++ according to the guidelines and samples given in the After Effects SDK (Adobe Corporation, 2002).

The developed plug-in is a well-behaved After Effects plug-in. The differences from the algorithm implemented in the R&D framework is that the opacity can be varied over time in the After Effects plug-in, and the inability to pick the average color of an area. The inability to pick average colors makes it hard to work with images that contain noise, like most video does.

The algorithm as implemented in this project attempts to optimize for speed, since it will potentially be applied to real-time digital video footage. Distances are used squared to avoid lengthy square root calculations for every pixel and the gaussian function is placed inside a lookup table that is changed only if the influence value changes. For further details about the implementation, refer to Kolås (2002).

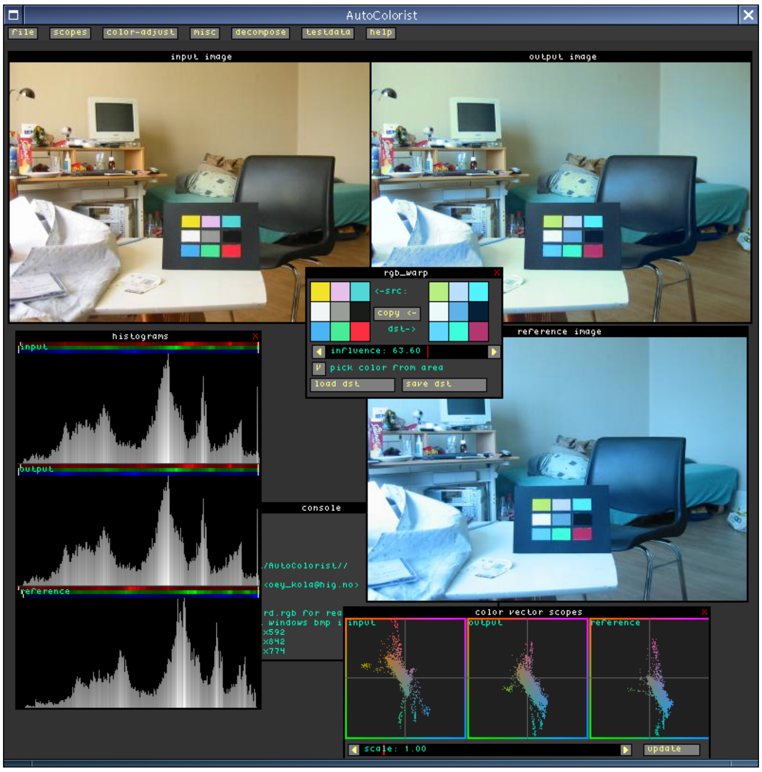

Figure 6. The user interface in the R&D platform.

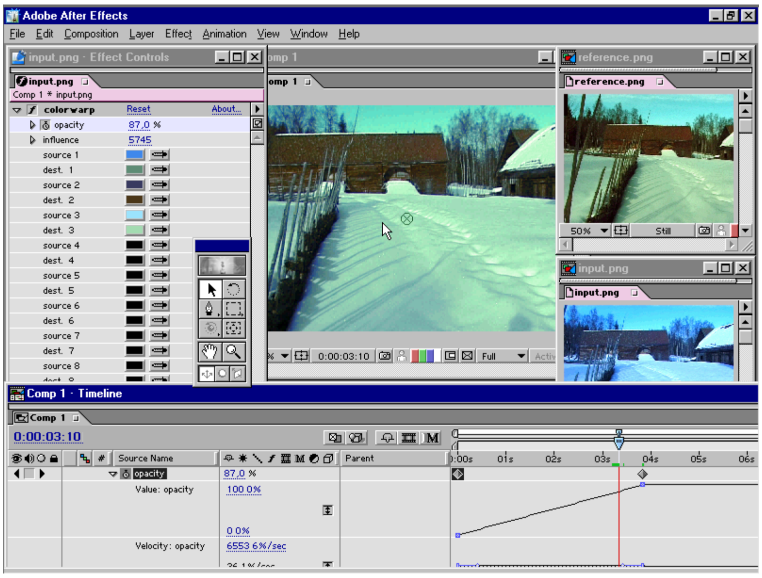

Figure 7. The color warp plug-in running under After Effects 5.5.

3.4. Discussion and results

Very encouraging results have been obtained using the proposed method, and we discuss here a few examples. Consider the source (left) and destination (right) images of Figure 8. For the sake of the illustration we show here only single frames of the shots. The varying color rendition was typically obtained by ”tricking” the white balance of the digital video camera. A few corresponding color pairs were chosen, having source and destination RGB values given in Table1. The standard deviation parameter of the warping algorithm was set to $\sigma = 15$. In the right column of Figure 8 we show the corrected images. While the two first rows show corrections based on color picked from the scene itself, the lower row shows a result using the colors of a test target.

Figure 8. Example results of the color warping algorithm. The colors of the source images (left) are warped using corresponding colors in the destination images (right). The colors in the resulting images (center) correspond quite well to those of the destination images. Better results could have been obtained by choosing more corresponding colors.

Table 1. Corresponding source and destination RGB colors for the example corrections shown in Figure 8.

”Face”	Source	Destination
Light skin	(195, 186, 143)	(219, 176, 140)
Skin in shadow	(128, 137, 87)	(125, 94, 66)
”Farm”	Source	Destination
Barn roof	(69, 65, 100)	(89, 47, 24)
Snow in sun	(156, 235, 251)	(163, 216, 171)
Snow in shadow	(62, 138, 244)	(88, 141, 115)
”Room”	Source	Destination
	(243, 228, 33)	(184, 239, 130)
	(229, 192, 235)	(185, 223, 252)
	(81, 215, 216)	(82, 242, 256)
	(242, 245, 245)	(236, 249, 249)
	(153, 158, 153)	(94, 178, 233)
	(26, 28, 25)	(5, 33, 56)
	(75, 180, 243)	(98, 216, 255)
	(72, 253, 152)	(60, 254, 223)
	(252, 47, 65)	(177, 55, 112)

We note that the transformation of the color spaces using the color target would probably have been better if the chosen colors more closely matched the colors in the scene. For instance picking the color of the wall, the floor and the bed would produce a destination image more similar to the source. This illustrates the advantages and limitations of using a test target instead of picking corresponding colors directly in the footage.

From this and other tests we conclude that for images taken on the same scene with different cameras or different angles the algorithm does a very good job of correcting the colors.

4. CONCLUSIONS AND PERSPECTIVES

We have described results of a collaborative research project aiming to develop methods and tools to improve the control of color information in the production and presentation of digital video. In particular we have addressed the problem of color correction and harmonization when different shots with varying color are to be edited together. Promising results have been obtained by a method in which corresponding colors are selected from the two shots. This is done either interactively directly in the captured scene, or using a color test target which have been introduced in the (physical) scene, typically. Then, based on the selected corresponding colors, we use an innovative color warping algorithm to transform one shot so that its colors are perceived to be similar to those of the other shot.

There are several potential directions for further work on this topic. One possibility would be to investigate the use of the proposed color warping algorithm for more typical color management tasks such as device characterization. One should then need to bear in mind that the warping algorithm tends to introduce unwanted geometrical distortions if the difference between the source and destination color spaces is large. It would be very useful to optimize the different parameters of the weight function, and to investigate alternative distance functions. Also, it could be interesting to compare our approach to advanced algorithms for automatic color correction, in particular within the field known as computational color constancy (Finlayson *et al.*, 1997; 2001, Cardei and Funt, 1999).

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