

Computer vision guided cross-projector color alignment on multi-projector displays

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Abstract

One of the problems the users of multi-projector displays have to deal with is due to the inherited differences and non-linearity in the output brightness versus the input signal of each CRT projector in the system. Manual color match alignment is usually possible, but it is time consuming and is not precise. This work discusses a possibility of performing such an alignment in an automated manner based on the application of computer vision. Two-level test patterns are shown by all projectors in the system at the same time, their digital images are continuously acquired by a video camera positioned in front of the display and compared on the host computer. Based on the results of the comparison, instructions are sent back to the projectors via RS-232 protocol to gradually change black/white balance or contrast until the test patterns match each other on all the projectors. The developed technique allows to achieve good results in color matching between the projectors on multi-projector displays within a relatively short time.

Keywords

CRT projector, multi-projector display, large screen projection, color

Introduction

CRT-based rear- or front-projected multi-projector displays are a popular way of achieving high resolution on large projection

areas. An example is Infinity Wall™ (I-Wall™) developed by the Electronic Visualization Laboratory (EVL) at the University of Illinois at Chicago (UIC), the National Center for Supercomputing Applications (NCSA) at the University of Illinois at Urbana-Champaign (UIUC), and the University of Minnesota and installed on the third floor of the Beckman Institute for Advanced Science and Technology in the Numerical Lab run by NCSA. The I-Wall is a versatile rear-projected display device that uses four screens to display multiple computer and media images. The device has a screen measuring 12' x 9' and is powered by four Electrohome Marquee 8500 projectors connected to an SGI Onyx with two Infinite RealityEngines running in either mono or active stereo mode. While in the mono mode, the I-Wall displays any X-Window onto a 2048 x 1536 pixels screen, making it a very high-resolution projection area.

One of the major inconveniences in using multi-projector systems such as I-Wall is due to the fact that even the high-end CRT projectors are not perfectly linear in the output brightness versus the input signal and each projector has its own gamma curve that differs from other projectors in the system. This phenomenon is due to the technology

used in cathode ray tubes and it results in the *mosaic effect* as seen on the projection screen: all the projectors produce slightly different color shades for the same input color and therefore the entire screen is visually not perceived as one large projection area, but rather as few very distinctive smaller regions. This has a negative contribution to the overall quality of the images shown on the display and helps to break the illusion of the immersion in 3D applications.

CRT projectors, particularly those developed by Electrohome Limited and now distributed by Christie Digital Systems, Inc., can be manually aligned to match each other's colors within certain limits via the brightness, contrast, white, and black balance adjustments. The procedure, however, is time consuming and usually results in an imprecise color matching anyway. This work discusses a possibility of performing such an alignment in an automated manner based on the application of computer vision.

Technique

The basic idea of the proposed technique is to capture and analyze in real-time test patterns produced on the host computer and displayed by the projectors and to submit appropriate adjustment instructions back to the projectors via RS-232 protocol. Test patterns in this study consist of two rectangles with different levels of gray. The instructions to the projectors are to increase/decrease black/white balance for a given color channel and the overall contrast value on each projector individually and are based on the results of the test patterns comparison. One projector serves as the master projector, all others (slaves) are adjusted to match the master's colors. Brightness and contrast levels on the slave

projectors are reset to 50% and 60% respectively before the alignment begins. Once the test patterns are shown, instructions are sent to all projectors to shut down the green and blue guns and to the slave projectors to switch into the color-balancing mode. Thus, only the red guns are active and they are adjusted until the brightness of the dark and bright rectangles on each slave projector matches those on the master projector. The same routine is then repeated for the remaining two color channels.

Test patterns

The first step in the proposed alignment procedure is to generate suitable test patterns and to project them by each projector on the screen. A simple test pattern consisting of two filled with different levels of gray shade rectangles is projected by each projector near the center of the I-Wall's screen as shown in Fig. 1. The darker rectangle has the value of 70 in each of its 3 color channels and is mainly used to align the black level, the brighter rectangle has the value of 230 and is primarily used to align the white level. One of the projectors (the upper-left in this case) is manually aligned to look reasonably good and serves as the master projector. It is important to make sure that the settings on the master projector are such that the slave projectors can match the output of the master projector.

Two-level test pattern with very distinctive levels of brightness in each region is chosen to insure that the gamma curve of each color channel on each projector will match at least at two distinctive levels of brightness. This, of course, does not guarantee that the gamma curve will match between the levels, but an introduction of additional levels of brightness in the test pattern would significantly raise the complexity of the alignment procedure.

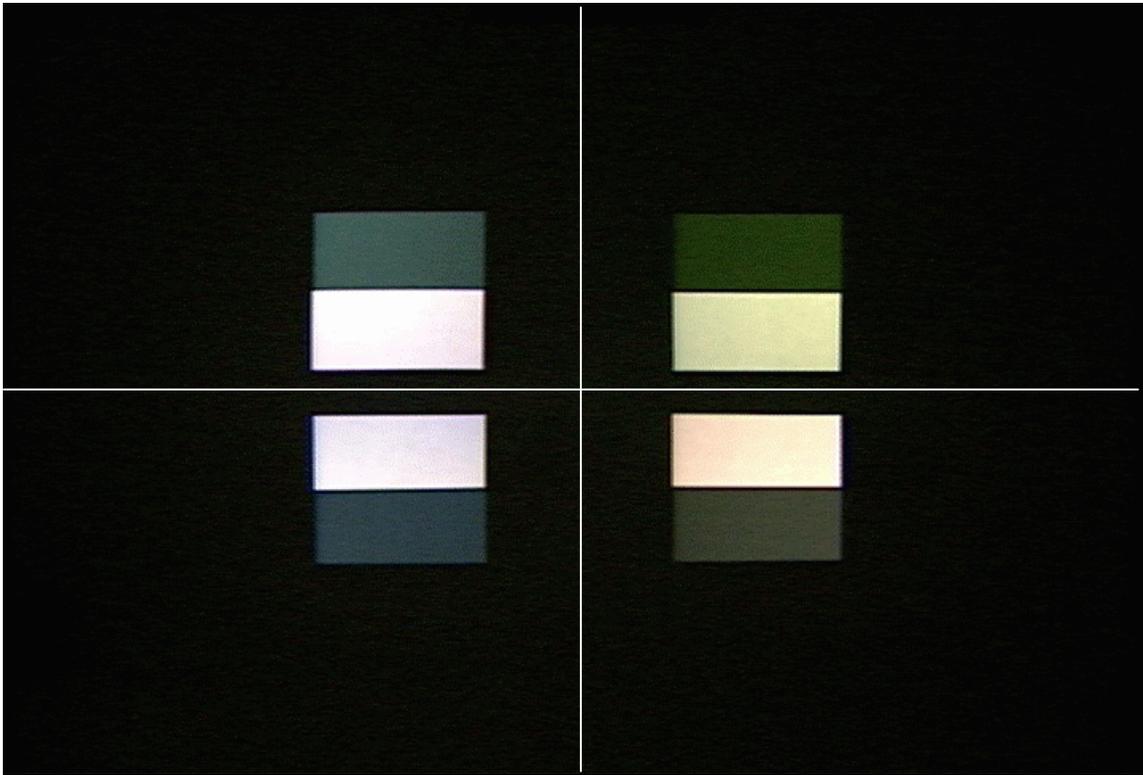


Fig. 1. Test patterns as seen on the I-Wall. White lines are drawn to show the sub-division of the screen between 4 projectors. The patterns look differently due to the color misalignment in the projectors.

Image acquisition

The second step in the procedure is to acquire digital images of the test patterns projected on the display. This is done in real-time with a help of a video camera placed in front of the screen few feet from its surface and aligned in such a way that all the test patterns are visible in a single image and are centered to match the alignment rectangles in the video processing software as shown in Fig. 2. Real-time video digitizing is done on an SGI O2 workstation. Two different color video cameras were tested: consumer-level SONY CCD-TR716 and a broadcast quality SONY DXC-637 equipped with Fujinon Aspheric 16x power-zoom lens. It was found that the quality of the video acquired by SONY CCD-TR716 is not suitable for this application due to the

very high level of noise, imprecise color reproduction, and inability to adjust the refresh rate of the CCD to eliminate the vertical refresh patterns from the projectors. From the other hand, SONY DXC-637 has proven to be a suitable one. It is important to point out that even the broadcast quality camera does not allow to capture the exact colors from the projected screen because it has its own color gamut and color representation capabilities that are different from those on the projectors, therefore some undesirable color distortion takes place during the image acquisition. This effect can be minimized via the camera calibration, but cannot be completely eliminated.

Once a video frame from the camera is digitized, it is copied to the shared memory arena in order to make it available for the image processing application.

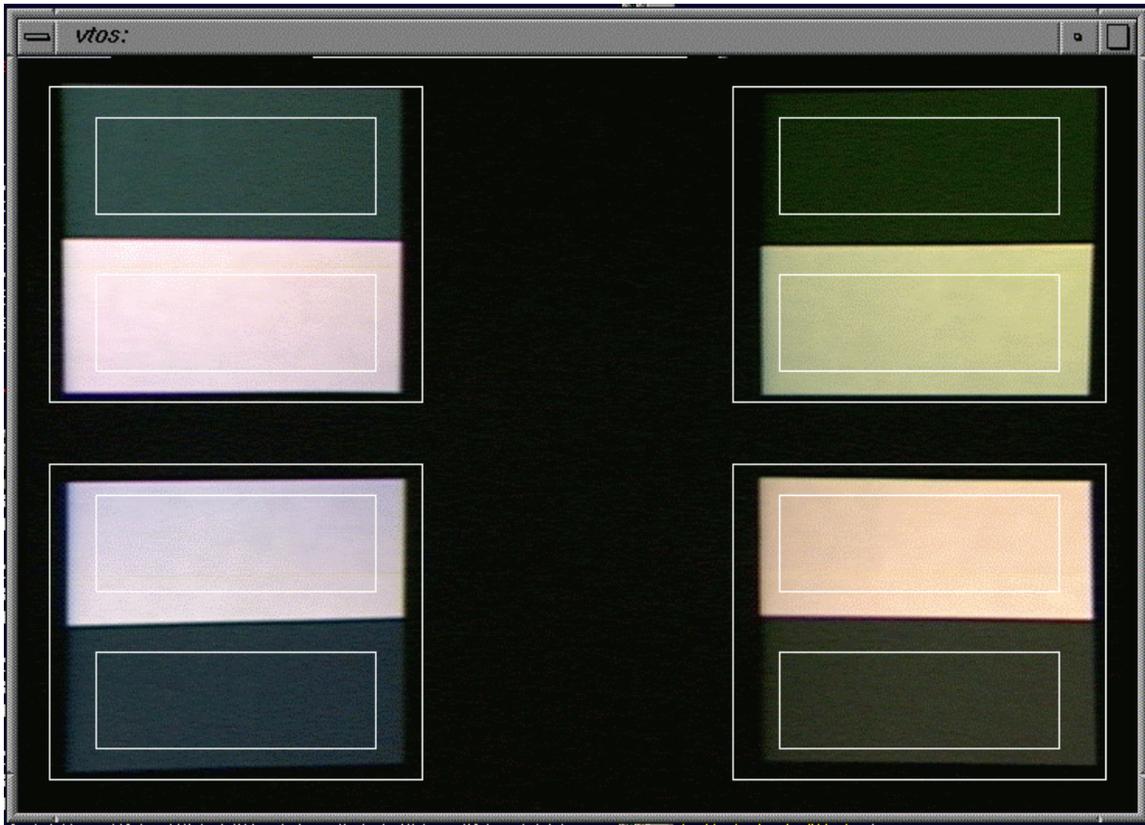


Fig. 2. Video frame captured and digitized on the host computer. Test patterns in the digitized image are aligned with the alignment rectangles in the video processing software.

Image processing

The third step in the alignment procedure is to extract some statistics from the digital images of the test patterns. Image processing software runs independently from the video digitizing routine. It accesses the shared memory arena where the current video frame is stored and copies it to its local memory buffer so the video capturing application does not have to wait until each frame is processed. Typically image processing routine runs slower than the video digitizer and therefore it skips some frames, which is generally not a problem for this application.

Very simple image processing takes place: average values of brightness for each gray

rectangle from each test pattern are computed for all color channels, assembled into UDP packets (separate for each projector), and sent over the network to the workstation running the actual alignment procedure. This is done without any regards to the current state of the alignment procedure and it is up to the alignment routine to decide if a given UDP packet has to be processed or discarded. The system is implemented in this way only because of the specifics of the hardware setup at NCSA's I-Wall; the projectors alignment procedure itself is computationally inexpensive and can be easily integrated with the image processing routine. In fact, a better design approach would be to merge all 3 processes (digitizer, image processor, and alignment) into one routine.

Communication with projectors

Electrohome Marquee 8500 series projectors with software version 4.2 and 3.x were used in this study. The projectors are equipped with RS-232 ports and are sequentially connected to each other and to the serial port of the host computer. Each projector in the system has a unique identification number (ID) that allows accessing any individual projector in the system over the same cable. The RS-232 instructions for the projectors with the software version 2.0 and higher enable the host computer to be programmed to emulate a projector keypad [1]. For example, to increase the brightness value by 2%, the following sequence of keypad instructions must be submitted to the projector: BRITE, UP, UP, UP, UP, UP, EXIT. The following sequence of the keypad instructions is used to switch projectors into the “utility / color balance / red color” mode: UTIL, K9, Ka, Kb, Kc, Kd, K1, K4, COLOR. Here Ka-Kd represent the digits of the password set to restrict access to the UTIL settings of the

projector. This approach is not particularly very convenient, however this is the only option available in the software version 2.0. Projectors with the software version 4.0 and higher provide a simpler and more robust protocol [2] (not used in this study).

Each keypad message transmission (software version 2.0 and higher) consists of a key start message followed by a key message itself. Both the key start message and the key message contain a header and a body embedded in the transport layer that also includes checksum. The header in the key start message contains the destination address (unique ID of the projector) and several mandatory bytes. The header in the key message contains the message destination and message return addresses. The body in the key start message includes 2 mandatory bytes and the keypad type byte. The body in the key message contains the command byte, the key code byte, and the keypad type byte. The following C code was developed to generate the key start message and the key message:

```
enum p_key          /* keys on the remote control */
{
    STB_ON, STB_OFF, SOURCE, RECALL, MUTE, VOLUME, CONTRAST, K0, K1, K2,
    K3, K4, K5, K6, K7, K8, K9, UP, DOWN, EXIT, ENTER, LEFT, RIGHT, STAR,
    PROJ, NUM, COLOR, TINT, DETAIL, BRITE, PIC, GEOM, CONV, HELP, UTIL
};

unsigned char p_code[] = /* key codes */
{
    0x3C, 0x0C, 0x2D, 0x22, 0x38, 0x1A, 0x02, 0x08, 0x0A, 0x3A, 0x12, 0x27,
    0x17, 0x3F, 0x2B, 0x1B, 0x33, 0x37, 0x31, 0x23, 0x0B, 0x0D, 0x15, 0x34,
    0x04, 0x03, 0x0E, 0x3E, 0x16, 0x32, 0x2C, 0x26, 0x2A, 0x0F, 0x1C
};

/* returns number of bytes in the key start message and fills in
   buf with the key start message for the projector proj */
int proj_genStartCode(int proj, unsigned char *buf)
{
    int i = 0, cs;

    buf[i++] = 0x01; cs = 0;          /* transport layer byte */
    buf[i++] = 0x08; cs += buf[i-1]; /* header byte 1 */
    buf[i++] = 0x3C; cs += buf[i-1]; /* header byte 2 */
}
```

```

if (proj == 1) {
    /* message destination */
    buf[i++] = 0x1B; buf[i++] = 0x81; cs += buf[i-1] - 128;
} else { buf[i++] = proj; cs += buf[i-1]; }

buf[i++] = 0x10; cs += buf[i-1]; /* header bytes */
buf[i++] = 0x00; cs += buf[i-1];
buf[i++] = 0x63; cs += buf[i-1]; /* body bytes */
buf[i++] = 0x30; cs += buf[i-1];
buf[i++] = 0x24; cs += buf[i-1];

cs = cs % 256; /* checksum */
if ( (cs == 0x01) || (cs == 0x0E) ||
      (cs == 0x11) || (cs == 0x13) || (cs == 0x1B) ) {
    buf[i++] = 0x1B; buf[i++] = cs + 128;
} else buf[i++] = cs;

buf[i++] = 0x0E; /* end of message */

return i; /* return number of bytes in the key start message */
}

/* returns number of bytes in the key message and fills in
   buf with the key message key for the projector proj */
int proj_genMessageCode(int proj, enum p_key key, unsigned char *buf)
{
    int i = 0, cs;

    buf[i++] = 0x01; cs = 0; /* transport layer byte */
    buf[i++] = 0x08; cs += buf[i-1]; /* header bytes */
    buf[i++] = 0x3C; cs += buf[i-1];

    if (proj == 1) {
        /* message destination */
        buf[i++] = 0x1B; buf[i++] = 0x81; cs += buf[i-1] - 128;
    } else { buf[i++] = proj; cs += buf[i-1]; }

    buf[i++] = 0x10; cs += buf[i-1]; /* header bytes */
    buf[i++] = 0x00; cs += buf[i-1];
    buf[i++] = 0x63; cs += buf[i-1]; /* body bytes */

    if (key == K8) {
        /* key code byte */
        buf[i++] = 0x1B; buf[i++] = 0x9B; cs += buf[i-1] - 128;
    } else if (key == COLOR) {
        buf[i++] = 0x1B; buf[i++] = 0x8E; cs += buf[i-1] - 128;
    } else { buf[i++] = p_code[key]; cs += buf[i-1]; }
    buf[i++] = 0x24; cs += buf[i-1];

    cs = cs % 256; /* checksum */
    if ( (cs == 0x01) || (cs == 0x0E) ||
          (cs == 0x11) || (cs == 0x13) || (cs == 0x1B) ) {
        buf[i++] = 0x1B; buf[i++] = cs + 128;
    } else buf[i++] = cs;

    buf[i++] = 0x0E; /* transport layer */

    return i; /* return number of bytes in the key message */
}

```

Standard UNIX port IO mechanism is used to submit the instructions (the key start message followed by the key message) generated by these functions. It is necessary, however, to make sure that the projector instructions buffer is not overloaded with the instructions. If this happens, it may be necessary to restart the projector before it can accept new instructions.

Projector alignment rules

The final step in the alignment procedure is to continuously submit an appropriate set of instructions to the slave projectors until they are aligned with the master projector. The projector alignment routine is implemented in the form of two nested loops that are executed until the alignment is complete. The external loop is responsible for setting an appropriate color to be aligned (red, followed by green, followed by blue). The internal loop is executed until the given color on all slave projectors matches the same color on the master projector at two different levels of brightness.

While in the internal loop, the application receives and processes the UDP packets from the image processing routine. If the packet corresponds to the master projector, it is stored locally for the comparison with the packets from the slave projectors. If the packet is from a slave projector, it is compared with the stored master data for the current color channel and a decision is made what instructions to send to the corresponding slave projector. The following 9 rules are used to make such a decision:

1. If the brightness of both the dark and bright rectangles on the slave projector is the same as that on the master projector, the corresponding slave projector is considered to be aligned for the given color channel and no action is required.

2. If the brightness of both the dark and bright rectangles on the slave projector is higher than on the master projector, an instruction is sent to the slave projector to decrease the value of its black level.
3. If the brightness of both the dark and bright rectangles on the slave projector is lower than on the master projector, an instruction is sent to the slave projector to increase the value of its black level.
4. If the brightness of the dark rectangle on the slave projector matches the brightness of the dark rectangle on the master projector and the bright rectangle on the slave projector is brighter than the bright rectangle on the master projector, an instruction is sent to the slave projector to decrease the value of its white level.
5. If the brightness of the dark rectangle on the slave projector matches the brightness of the dark rectangle on the master projector and the bright rectangle on the slave projector is darker than the bright rectangle on the master projector, an instruction is sent to the slave projector to increase the value of its white level.
6. If the brightness of the bright rectangle on the slave projector matches the brightness of the bright rectangle on the master projector and the dark rectangle on the slave projector is darker than the dark rectangle on the master projector, an instruction is sent to the slave projector to increase the value of its black level.
7. If the brightness of the bright rectangle on the slave projector matches the brightness of the bright rectangle on the master projector and the dark rectangle on the slave projector is brighter than the dark rectangle on the master projector, an instruction is sent to the slave

projector to decrease the value of its black level.

8. If the dark rectangle on the slave projector is darker than the dark rectangle on the master projector and the bright rectangle on the slave projector is brighter than the bright rectangle on the master projector, an instruction is sent to the slave projector to increase the value of its black level.
9. If the dark rectangle on the slave projector is brighter than the dark rectangle on the master projector and the bright rectangle on the slave projector is darker than the bright rectangle on the master projector, an instruction is sent to the slave projector to decrease the value of its black level.

Some of the rules can be merged, however in this form they are easier to manage. Rules 4 and 5 are the only rules that apply to the white balance adjustment. The black level balance provides us with a finer tuning possibility than the white level balance. Also, it is necessary to know the current level of the white balance for each slave projector and to make sure that it does not reach the limit. This is achieved by resetting its value to 50% before the alignment and counting how many times an instruction to adjust the white balance was submitted for each projector. If rule 4 is applicable and the white balance for a given slave projector reaches 0%, its value is reset to 50% and the value of the contrast on that projector is decreased by 5%. If rule 5 is applicable and the white balance for a given slave projector reaches 100%, its value is reset to 50% and the value of the contrast on that projector is increased by 5%. Contrast manipulations, however, result in the misalignment of the previously aligned color channels (if such exist). Therefore, once the contrast is changed while adjusting green or blue guns, the external loop is reset and the alignment

procedure is repeated again for all colors.

Even this sophisticated set of rules does not guarantee that the colors on the slave projectors will converge to match the colors on the master projector. This may happen, for example, when slave projectors are much older than the master projector and therefore cannot reproduce highly saturated and contrast colors on the master projector. The solution is to realign the master projector so it produces less saturated output.

Results and discussion

Tests were conducted on the I-Wall at NCSA to verify the suitability of the developed technique for its practical utilization. A picture of the I-Wall (Fig. 3a) was taken when the I-Wall's projectors were not properly aligned. As seen from the picture, there is a significant difference in the colors among the projectors. Fig. 3b presents a picture taken after the alignment procedure was performed using the upper-left projector as the master source. The color difference between the aligned projectors is almost unnoticeable. The entire alignment procedure may take anywhere from 5 to 20 minutes depending on the degree of the misalignment. Also, it was found that eliminating external sources of light in the lab helps to achieve slightly better results.

As it was mentioned earlier, it is very important to make sure that the settings on the master projector are such that the slave projectors can match them. In our setup, the master projector was newer than the slave projectors and its initial settings were such that the slave projectors could not match the master's colors neither by a human nor by this technique no matter what parameters were changed. As a result, both the brightness and contrast on the master projector had to be decreased.

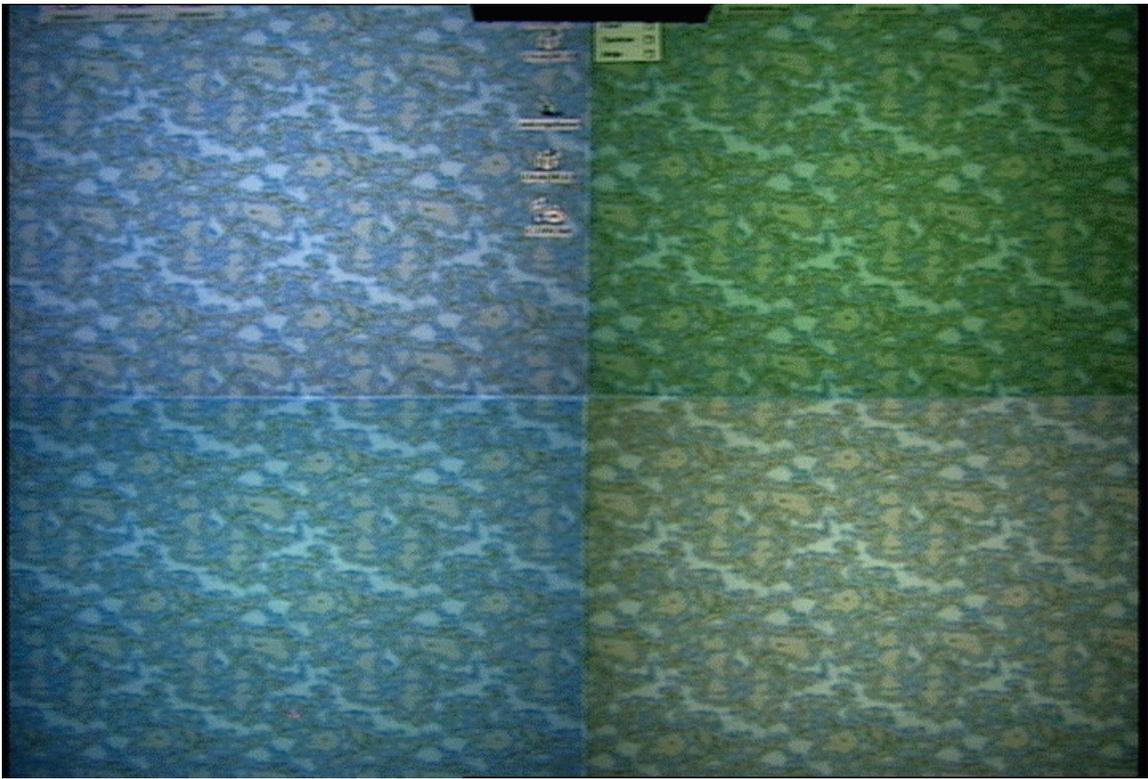


Fig. 3. a) before and b) after the alignment.

Although, even when there are no noticeable differences in the color shades across all the projectors in the system, the mosaic effect is still present due to the non-uniform distribution of luminance across the screen. The maximal luminance peak for a projector is located along the direction perpendicular to the projector and diminishes with a Gauss-like function orthogonal to this direction. Four luminance peaks are observed on a four-projector screen and they form a visually noticeable cross-like dark region in the middle of the screen. It is not possible to eliminate this artifact with the present technique since there is nothing available in the projectors to adjust the uniformity of its luminance. A technique to deal with this artifact is described in [3].

Once aligned, projectors tend not to preserve their settings for a long period of time. This unpleasant feature especially becomes noticeable when the projectors are relatively old, there are some sudden temperature changes in the surrounding environment, the projectors are restarted, etc. Therefore, the color match realignment is usually needs to be repeated from time to time.

A broadcast-quality video camera was used in the present study allowing the adjustment of the projectors to match the colors manually set on one of them. However, in order to adjust the color temperature to the correct absolute value, a device, such as Minolta Chroma-Meter CS-100 tristimulus colorimeter, that does the absolute color temperature measurements is required.

Conclusions and future work

Presented in this report computer vision based color alignment approach allows achieving relatively high degree of color matching between the projectors on multi-projector displays. However, this is a relatively expensive solution since it

requires a broadcast quality video camera. If frequent realignment is required, this equipment needs to be present permanently. Also, this is not a perfect solution because the camera, even a high quality one, distorts the colors.

There are still some experiments to be tried out. For example, in the present study the camera is installed in front of the display, thus registering the transmitted light. It is not clear, however, if the system will perform in the same way when the camera is installed behind the screen, thus registering the reflected light. Also, it is not possible to apply this approach directly in a CAVE-like environment since the algorithm requires the test patterns from all the projectors to be present in the same image. The following setup is currently considered: a camera is located in the middle of the CAVE on a movable platform that can be turned around to point the camera in the direction of a given wall. First, it is pointed towards the master wall where an appropriate test pattern is shown so that an appropriate set of parameters for each color channel can be computed. Next, the camera is manually turned to point towards one of the slave walls where the same test pattern is displayed and the alignment procedure is then performed for this projector only. The same then can be done for each slave wall. The problem with this approach may be with the floor since it is usually rear-projected and the camera would cast a shadow.

One of the issues that have not been addressed in the current study is the location of the test pattern on the screen. Because of the non-linearity of the projector's output across the screen, average values of RGB can be different for different regions of the display. Thus, they will be higher for the center and lower for the sides.

The most difficult part of the work was to select appropriate projector alignment rules.

It is not clear if the proposed rules are the most optimal ones, especially the last two. Additional experiments are required to eliminate those situations when the projectors cannot converge to reproduce both brightness levels at the same time. It is also interesting to generalize the proposed rules so more than 2 levels of brightness can be matched.

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