High-Speed RGB+IR Projector based on Coaxial Optical Design with Two Digital Mirror Devices

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ABSTRACT

Sensing and display are expected to be closely integrated with the rise in new projector applications that manipulate the appearance of the real world. To meet this demand, this study proposes a novel high-speed RGB+IR projector which introduces sensing in invisible wavelengths based on a projector-camera configuration—a long-established computer-vision technology—and can manipulate visible display images flexibly based on its sensing results. Two mounted digital mirror devices (DMDs) control 24-bit RGB and 8-bit IR images simultaneously. Our original optical engine aligns the images coaxially with high precision while maintaining a compact configuration and high-power projection. Our projector achieves a high frame rate of up to around 1,000 fps, the images being transferred from the computer with a latency of several milliseconds.

1 Introduction

In recent applications such as projection mapping, projectors have been used to visually augment surfaces, opening new possibilities for the visual world. In these scenarios, the projection target is no longer limited to a flat, white screen and the projected image needs to be controlled based on various target surfaces by integrating visual sensing to manipulate the scene.

The speed of projection is one of the key factors in such applications, a high-frame-rate projection being required to merge the projected image and the moving target without perceived misalignment. To meet this requirement, 1,000-fps projectors have been developed in recent years [1, 2], dynamic projection mapping (DPM) being a promising application for such devices. With the rise of high-speed projectors, the level of DPM has evolved [3-7]. However, conventional applications can suffer from attaching markers to targets or restricting the target to a face or plane as sensing in conjunction with DPM remains limited.

Conversely, projectors are known to play powerful roles in both display and visual sensing—projector-camera systems can efficiently acquire shape, spectral reflectance, light transport, transient image, etc. [8-12]. In particular, shape is important in various applications such as projection mapping. The introduction of such sensing in applications has been eased as products comprising projectors with integrated cameras have been developed [13]. If the projected target is static, sensing can be applied using a projector-camera system, the display application being applied in turn. However, in a dynamic scene, this approach is not acceptable, as the sensing and display needs to be handled simultaneously. Consequently, applications in dynamic environments such as DPM have not fully exploited projector-camera sensing technologies.

Based on this background, we aim to develop a new high-speed projector for a wider range of applications. To meet this objective, we focus on allowing the sensing to leverage the projector-camera sensing technologies that are already well-established in the field of computer vision. Moreover, we explore the possibility that such projector-camera sensing can be achieved without interfering with the projection display.

One possible approach is to embed the patterns for sensing in the projected visible images for display [14]. However, in this approach the pattern is limited to a binary image and the displayed image has low contrast. Another idea is to combine a visible red/green/blue (RGB) projector for display with an infrared (IR) projector for sensing. Although an IR projector has been developed, its application has been mainly limited to support training with a night vision scope [15]. An RGB+IR projector has also been developed, but it has been used primarily for light communication [16]. Moreover, because it uses only one digital mirror device (DMD), the RGB and IR images cannot be controlled independently. In addition, the frame rate of these projectors is not sufficiently high for applications in the dynamic scenes mentioned above.

Our proposed projector consists of two DMDs and can control 24-bit RGB and 8-bit IR images independently at a high frame rate of approximately 1,000 fps, the RGB and IR images being coaxially aligned using a specialized optics engine. This paper details the

Fig. 1 Developed high-speed RGB+IR projector

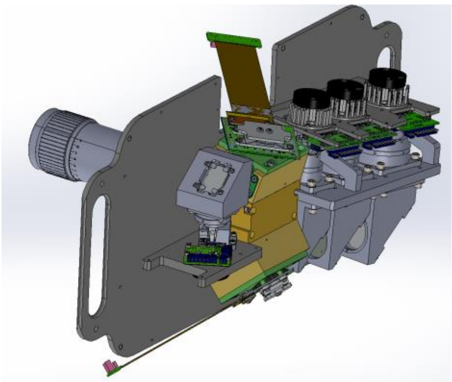

Fig. 2 Mechanical design of the optics engine

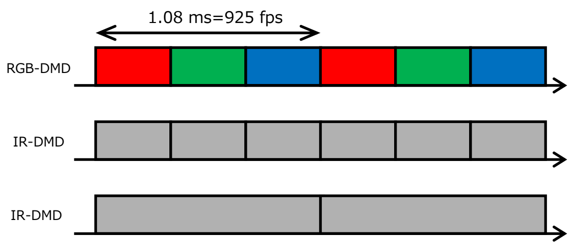

Fig. 3 Example of the projection control

configuration and its performance.

2 Methodology: High-speed RGB+IR projector

Figure 1 shows the developed projector, with two DMDs mounted, one DMD controlling a visible RGB image, and the other DMD controlling an invisible IR image. We use the same DMDs with a resolution of 1024 × 768 pixels. The light sources are high-power red, green, blue, and infrared (IR) LEDs. In particular, we divert the IR LED (850 nm)—developed primarily for illumination in machine vision—to our projection application.

The RGB and IR images are aligned coaxially using our original optics engine. Figure 2 shows the mechanical design of the designed optical engine which is designed from scratch and optimized for the light sources used to keep their output power as high as possible. Our engine integrates illumination optics for RGB and IR lighting separately, combining their images after the DMD reflections by means of a beam splitter. Compared with the engine combining four-channel lights in one illumination optics system before the DMD reflection, we find our solution to be more compact.

We also optimize the projection optics to use as few lenses as possible while maintaining low distortion, small color correction, shorter overall length, while still meeting the tolerance requirements for MTF against manufacturing errors. We also design the optics to maintain the same focal range for the RGB and IR images by considering the effects of different wavelengths.

A housing with cooling devices—including fans and heat sinks—is designed using thermal simulation. We simulated the airflow inside the projector and confirmed that the cooling performance met the requirements of the DMDs and LEDs.

The maximum frame rates of the 24-bit RGB and 8-bit IR projections are 925 fps and 2777 fps, respectively. The RGB and IR-image projections can be synchronized, and their frame rates can be changed based on the applications. Two examples of projection control are shown in Fig. 3. In the one example, the IR image is updated every time each channel is updated in the RGB image. In the other example, the IR image is updated every time the 24-bit RGB image is updated. The high-frame-rate projection is achieved using the same principle introduced in conventional high-speed projectors [1, 2]. It closely coordinates the DMD control with light-source modulation to realize a very short projection time. However, because of the RGB and IR-image synchronization, the maximum frame rate became slightly lower than the conventional high-speed projectors [1, 2]. Two images are transferred from the computer to the projector with low latency via an optical fiber connection.

3 Results and Discussion

Figure 4 shows the results of the RGB and IR-image alignment. In the figure, the same chessboard patterns are projected. The degree of vertical misalignment—indicated by the red arrow—and horizontal misalignment—indicated by the blue arrow—are nine and three pixels, respectively.

The results of the homogeneity evaluation are shown in Fig. 5. We measured the illuminance of an RGB image

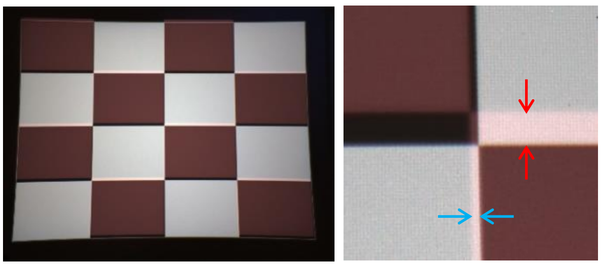

Fig. 4 RGB and IR-image alignment

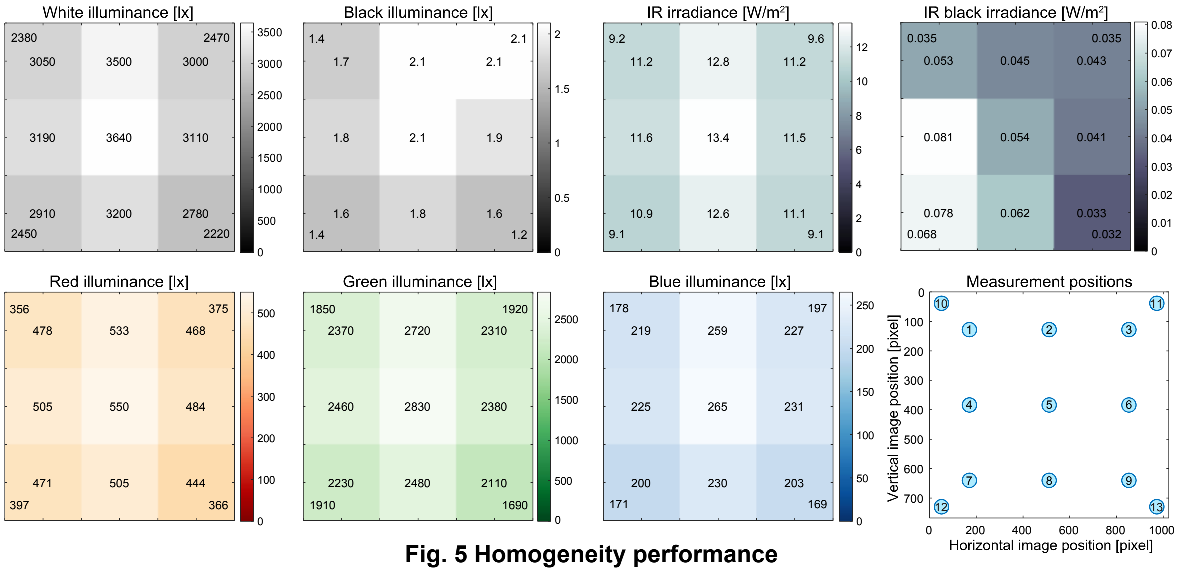

Fig. 5 Homogeneity performance

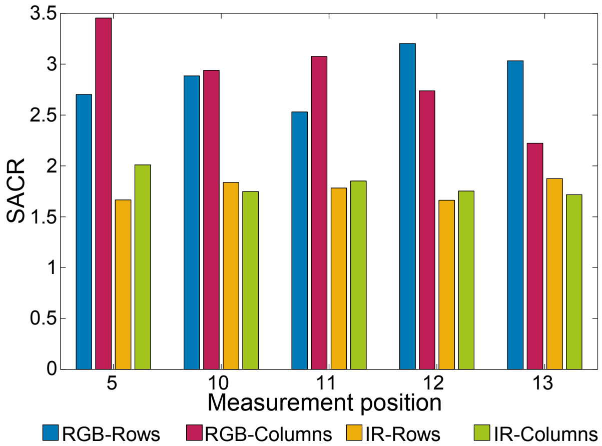

Fig. 6 Small-area contrast ratio

and irradiance of an IR image at 13 locations, in accordance with the IEC 61947-1 standard. In this evaluation, the light source provided maximum power and was not modulated. The results showed that the developed projector achieved acceptable homogeneity performance and high-power projection.

The contrast ratio can be evaluated using the Eq. (1):

$$SACR = \frac{I_{\max}}{I_{\min}}. \quad (1)$$

This is the small-area contrast ratio. We evaluated this by changing the stripe patterns in the horizontal and vertical directions, the pattern alternating between black and white bars for every pixel. The results are shown in Fig. 6, where the '*Rows*' and '*Columns*' indicate the results of vertical and horizontal stripe patterns, respectively. Measurement positions are shown in Fig. 5. The IR performance is lower than the actual performance as the sensitivity of the camera used was low for the IR range and is noisy. Moreover, the lens in the camera was not designed for IR images, having additional blur in the captured image.

Distortion is evaluated using the Eq. (2):

Fig. 7 Projection results

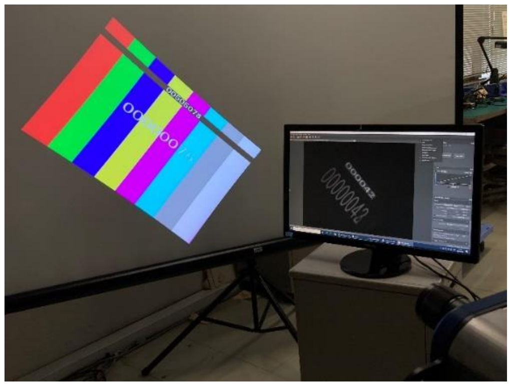

Fig. 8 High-speed projection result

$$D = \frac{\tilde{y}-y}{y} \ [\%],$$

where $\tilde{y}$ is the size of the measured image and y is the ideal image size without distortion. The horizontal distortions of the RGB and IR images were 3.6% and 3.7%, respectively. The vertical distortions of the RGB and IR images were 2.0% and 2.1%, respectively. Distortions in the diagonal direction in the RGB and IR images were 5.6% and 5.8%, respectively. The developed projector exhibited a throw rate of 1.9. The projected image was focused at a distance of 50 cm from the projector at a minimum.

Figure 7 shows the results projecting RGB image (center) and IR image (right) to mannequin (left). Figure 8 shows the high-speed projection result. In the figure, the RGB and IR images are projected at 925 fps and 2777 fps, respectively, onto the screen—that is, the RGB image is projected onto the screen, but the IR image is captured

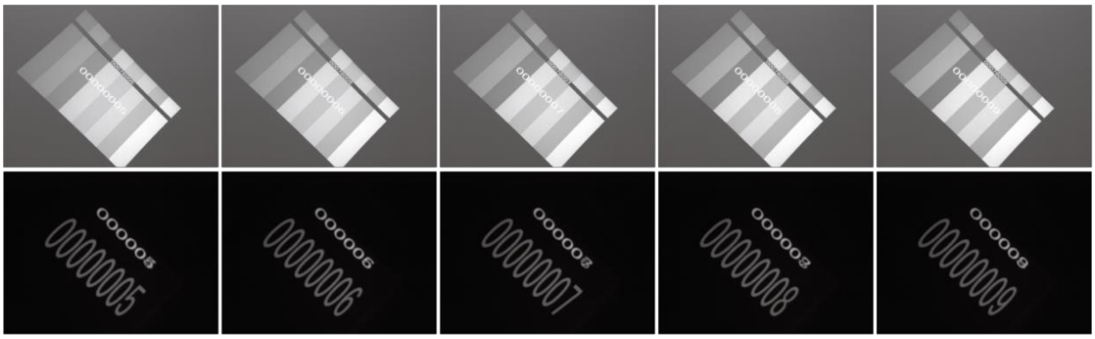

Fig. 9 High-speed RGB (Top) and IR (Bottom) projection results captured using two cameras

using a camera placed near the projector and shown on the monitor. As demonstrated in the figures, two types of images are projected, one of which is invisible.

Figure 9 shows the results capturing the projected images by 500-fps monochrome cameras. Cameras were not synchronized with the projector. The projection frame rate was 500 fps.

4 Conclusions

This paper presents a new type of projector that can project 24-bit RGB and 8-bit IR images independently and simultaneously. The projector can update the images at high frame rate with low millisecond-order latency. The two-DMD configuration allows the user to independently control the two types of images. Our original optical engine could project them by means of highly accurate coaxial alignment. Various evaluation results show that this projector could be introduced in practical applications by manipulating the projected images dynamically based on the projector-camera sensing results. An example application is DPM onto the entire area using a depth image and markerless target tracking [17].

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