A Low-Latency Image-Warping Projector with Application to Dynamic Projection Mapping

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ABSTRACT

This paper reviews recent efforts of the author's group in developing a projection system with a low-latency image-warping capability. Applications including a caribration-free and marker-free dynamic projection mapping and interactive augmented reality systems are also described.

1 Introduction

One of key challenges in realizing an interactive system using projectors is to minimize the latency between motion and image presentation. Considerable effort has been devoted to develop special hardware to achieve low-latency projection [1, 2, 3, 4].

Many of such special systems make use of Digital Micromirror Device (DMD) as a spatial light modulator in the projector, which produces fast flapping binary patterns at a rate of up to tens of kHz. A sequence of fast flapping binary patterns is time-averaged by the human eye and perceived as an image. We refer to a set of consecutive binary patterns that represent a single color (or gray-level) image as a video frame.

The front door approach to achieve a low-latency projection is to increase the video frame rate. However, the increase of the video frame rate comes at the expense of significantly increased hardware costs and video rendering burdens.

This paper reviews a different approach taken by the author's group. With this approach, we do not resort to increasing the video frame rate as a means of reducing the latency. Instead, image warping is applied to each binary pattern so that projected images timely follows real-world motions. In the rest of this paper, a brief summary of this "binary frame warping" approach and its implementations is presented, followed by several application examples.

2 Binary Frame Warping Approach

In a common DMD projector, an input video frame is decomposed into bit plane patterns, which are sent to DMD in an predefined sequence such that the time average of the patterns equals to the original video frame. Our system works almost in the same manner, except that the decomposed pattern is warped before being sent to DMD.

Imagine that we are moving a rectangular surface in front of the projector, and its movement is measured by some kind of sensors. By applying a homography (i.e., 2D projective) warp such that the projected image is completely aligned to the surface, we can virtually simulate the situation as if the projector is rigidly coupled to and moving along with the surface. This approach applied to a 60-fps video offers a perceptual image quality comparable with the quality offered by 500-fps video projection [5].

Our first monochrome implementation [6] was built using a Texas Instruments DLP Discovery 4100 kit, which includes a 1,024×768-pixels DMD (DLP7000), a XILINX Virtex-5 FPGA, and an SDRAM. Homography warping, as commanded through USB 2.0 port, was implemented in the FPGA to warp the patterns prestored in SDRAM at up to 1,388 binary frames per second. Our latest full-color implementation [7] also adopts DLP7000 but incorporates a custom controller including a XILINX Kintex-7 FPGA, which warps input images provided through an HDMI port at up to 2,470 binary frames per second synchronously with the brightness control of RGBW LED light source.

3 Calibration-free and Marker-free Projection Mapping

Projection mapping onto a real-world object surface requires accurate registration between a projected image and the object surface. This is a challenge particularly when the object is moving dynamically. When a camera is used to measure the surface movement, precise positioning or geometric calibration of the relative pose between the camera and projector is commonly required.

In contrast, we applied our low-latency projection system to calibration-free projection mapping onto a markerless plane [8]. We applied a closed-loop alignment technique, in which the projected content as well as the surface texture is tracked by a camera and the warping parameters of the projected content are controlled to minimize the misalignment.

A key challenge was how to achieve simultaneous tracking of the projected content and the surface texture separate from a single camera image. We inserted checkerboard-like fiducial code patterns such that they appear in every sixth binary frame in 2,400 binary fps projection. The proposed tracking algorithm first aligns the surface texture in the camera image, and then extracts the code pattern to track the projected content geometry.

4 Interactive Applications

4.1 Physics-based Interaction with Projection

We implemented a fast projection mapping system that enables dynamic interaction with projected content through the movement of a handheld surface onto which the content is projected [9]. The projected dynamic objects interact with static shapes hand-drawn or printed on the surface under the effect of virtual gravitational and inertial forces generated according to the surface movement.

A key feature of this system lies in that the physics-based animation is rendered at up to 60 fps while the projection mapping control is done at 400 fps. Despite the existence of a significant latency in rendering the animation, the accurate alignment of the rendered result to the surface ensures consistent interaction between the dynamic projected objects and the static on-surface shapes.

4.2 Virtual Air Hockey with Transformable Mallet

Although there existed many attempts to apply augmented-reality (AR) techniques to enhancement of air hockey games, the mallet (also called paddle or striker) was always a physical one, presumably because the movement of the mallet is more difficult to predict than that of the puck, and when the prediction becomes wrong, it is clearly perceived. We applied our projection system to visualize the mallet shape as well, allowing infinite possibilities in game design [10].

4.3 Position-Dependent Strobe Lighting

A totally different type of application is to use the projector as a strobe lighting in which strobe periods can be defined per pixel. We applied such a projection-based strobe lighting to enhancement of the well-known illusion of “levitating” water drops [11]. By illuminating arrays of water drops dripped at a regular time interval, a part of projection area renders, for example, slowly rising water drops, while another area renders slowly falling ones. Controlling the image warp by a hand motion tracker enables interactive manipulation of those areas.

5 Conclusion

This paper reviewed our recent efforts in developing and applying a low-latency projection system featuring an embedded binary frame warping engine. Because the proposed technique can be applied to a low-price range of DMD whose binary pattern rate is at most a few kHz, it is expected to contribute to realization of cost-effective interactive projection systems.

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References

[1] Kohei Okumura, Hiromasa Oku, and Masatoshi Ishikawa. Lumipen: Projection-based mixed reality for dynamic objects. In *Proceedings of 2012 IEEE International Conference on Multimedia and Expo*, pages 699–704, 2012.

[2] Ryuji Fuchikami. Real-time-measurement projection device and three-dimensional-projection measurement device. International Patent Application, PCT/JP2016/002302, 2016.

[3] Gaku Narita, Yoshihiro Watanabe, and Masatoshi Ishikawa. Dynamic projection mapping onto deforming non-rigid surface using deformable dot cluster marker. *IEEE Trans. Vis. Comput. Graph.*, 23(3):1235–1248, 2017.

[4] Amit H. Bermano, Markus Billeter, Daisuke Iwai, and Anselm Grundhöfer. Makeup Lamps: Live augmentation of human faces via projection. *Comput. Graph. Forum*, 36(2):311–323, 2017.

[5] Wakana Oshiro, Shingo Kagami, and Koichi Hashimoto. Perception of motion-adaptive color images displayed by a high-speed DMD projector. In *IEEE VR 2019 Workshop on Perception-driven Graphics and Displays for VR and AR*, 2019.

[6] Shingo Kagami and Koichi Hashimoto. Sticky Projection Mapping: 450-fps tracking projection onto a moving planar surface. In *SIGGRAPH Asia 2015 Emerging Technologies*, 2015. Article no.23.

[7] Shingo Kagami and Koichi Hashimoto. A full-color single-chip-DLP projector with an embedded 2400-fps homography warping engine. In *SIGGRAPH 2018 Emerging Technologies*, 2018. Article no.1.

[8] Shingo Kagami and Koichi Hashimoto. Animated Stickies: Fast video projection mapping onto a markerless plane through a direct closed-loop alignment. *IEEE Trans. Vis. Comput. Graph.*, 25(11):3094–3104, 2019.

[9] Shingo Kagami and Koichi Hashimoto. Interactive Stickies: Low-latency projection mapping for dynamic interaction with projected images on a movable surface. In *SIGGRAPH 2020 Emerging Technologies*, 2020. Article no.16.

[10] Shun Ueda, Shingo Kagami, and Koichi Hashimoto. MetamorHockey: A projection-based virtual air hockey platform featuring transformable mallet shapes. In *SIGGRAPH 2021 Emerging Technologies*, 2021. Article no.7.

[11] Shingo Kagami, Kotone Higuchi, and Koichi Hashimoto. Puppeteered Rain: Interactive illusion of levitating water drops by position-dependent strobe projection. In *SIGGRAPH 2019 Posters*, 2019. Article no.48.