Latest Research Trends on Computational Projection Mapping

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ABSTRACT

This invited talk will introduce the latest research trends of both fundamental technologies and applications on computational projection mapping. Especially, this talk will focus on dynamic projection mapping, in which a moving object is augmented by projected imagery, gathering more and more attentions recently. This talk is based on a state-of-the-art report presentation in Eurorgraphics 2018 by the author [2]. The main part of this extended abstract (especially Section 2 and 3) is configured by extracting the related texts from [2].

1 Introduction

Computational display is an active research field in computer graphics, computer vision, and optics research fields. It is defined as "the joint design of hardware and display optics with computational algorithms and perceptual considerations" by Masia et al. [1]. The computational display approach has been successfully improved image qualities of any types of displays including flat panel display, head-mounted display, and projection display, and add novel functionalities such as light field display. An interesting extension of this concept is computational projection mapping. Because projection surface is a component of the whole projection display system in projection mapping applications, there is a potential to enhance the image qualities of projection mapping by optimizing not only hardware, optics, and algorithms but also surface properties such as reflectance.

In this talk, I will introduce this emerging display concept, computational projection mapping, and show several outcomes in this field. In particular, dynamic projection mapping, in which a moving surface (both rigid and deformable) is used as a projection surface, is gaining more and more attentions. To realize a plausible and feasible projection mapping results, there are hard technical challenges. For example, extremely low latency projection is required. This talk will cover the state-of-the-art technologies tackling on these challenges. Note that recent trends in projection mapping research including the computational projection mapping works were summarized in recently published survey paper [2], which also introduces other types of computational projection displays such as:

- High dynamic range projection
- High resolution projection
- Increasing focal depth
- Light field projection
- Multispectral projection

Those who are interested in these topics, please refer to the survey paper [2].

2 Dynamic Projection Mapping

While projection mapping has been an active research field for a long time, most of the earlier research focused on the augmentation of static objects, or slowly and rigidly moving objects, since any dynamic projection system significantly adds up in system complexity and performance requirements. However, since the computational power of CPUs and GPUs evolved quickly according to Moore's law, and high-speed cameras and projectors are now becoming commercially available, more and more dynamic projection mapping systems have been published. These methods can be classified with respect to their degree of freedom when it comes to the dynamic components of the procam system. Most of the systems define dynamic in the sense that the scene rigidly transforms (or at least the non-rigid transformation is already known), or the projector or the camera is allowed to move. These approaches – although requiring significantly low latencies to generate convincing augmentations – can be supported by the application of known rigid geometry and potentially-available tracking information.

Much less work has been published with real-time projections onto fully non-rigid, dynamic and unknown moving projection surfaces. In the latter case, the complete surface shape has to be estimated either in 3D or at least 2D, while the overall system latency still needs to be kept in the order of a few milliseconds to avoid perceptual lagging of the superimposed projection.

2.1 Rigid Dynamic Projection

Methods for the augmentation of rigid dynamic objects do not require a full dense online surface reconstruction, but only a pose estimation of the projector with respect to the geometry to understand how the already known, geometrically rigid computer graphics needs to be rendered correctly by the devices.

Applying a visual marker achieves a stable pose estimation. However, markers attached on a projection surface disturb projected results, as we can see the markers as a texture of the surface. This issue is resolved by combining a radiometric compensation technique to visually cancel the markers. Other researchers replace the markers with tiny photosensors to measure the scanning timing of a projected beam from a laser projector. Due to the raster-scanning mechanism, the pixel coordinate of the projected beam is uniquely identified from the measured time information. Once more than six photosensors measure the scanning timings and identify these pixel coordinates, the pose of the surface is estimated

A method which uses a low-resolution online-reconstruction for projector registration was presented: The shape of an augmented object is measured on-line by triangulation using projected features and the corresponding camera pixel correspondences, then the iterative closest points (ICP) algorithm is used to estimate the six degrees of freedom (6DOF) movement which allows to register the projection to the current pose of the real object to augment. Another research group optimized projection images by solving the light transport matrix, which was derived from the 6DOF relations between each projector and the object measured by a Kinect depth sensor. A related method using an infrared camera was also presented. A method for optimal projector assignment for dynamically moving rigid objects using the normal vector information was proposed. A deformable motorized animatronic silicon head was augmented using multiple registered projectors to enhance its appearance by superimposing high-frequency details such as wrinkles which couldn't be generated by the deformation of the silicon skin alone. Although the system was able to project onto a non-rigid surface, the authors could only augment the head for known poses and a 3D scan and registration for each individual pose was required.

Overcoming the perceived lagging resulting from the inevitable end-to-end latency of such a system is also an ongoing research area. In one of the earliest approaches, Block-Matching has been used to predict the unknown motion of a human hand. Leveraging a 1,000 Hz high speed procams, a visual marker-based method achieves a very low latency registration. A stable marker position prediction is possible because the distance between the previous and current marker positions are short due to the small time difference (i.e., 1 ms).

2.2 Non-Rigid Dynamic Projection

A solution for dynamic projection mapping onto a deformable object is described by Punpongsanon et al.: It is realized by painting invisible markers based on infrared ink onto the surface, which, being measured by an infrared camera, are used to estimate the surface's non-rigid deformation and to adapt the projection accordingly. A high-speed camera is used to robustly track dot cluster markers drawn by the same invisible inks. Alternatively, retro-reflective markers are used to measure the surface deformation in the word of Fujimoto et al. However, a fully dynamic tracking is not achieved by this method. The dot cluster markers were extended to also allow the projection onto dynamic objects as shown by Narita et al.

A system to dynamically augment human faces using projection was presented by Bermano et al. It applies markerless human face tracking, estimates blend shapes describing the current expression, deforms a base mesh and applies a texture which is dynamically adapted depending on estimated expression, time, desired lighting, as well as the spatial location of the face. To simplify the overall processing pipeline, projector and camera were optically aligned allowing the whole augmentation pipeline to work in 2D space. The overall latency of the presented prototype is less than 10 ms. Although this might sound sufficiently fast, an extended Kalman filter (EKF) needed to be incorporated for motion prediction to keep the inevitable delay of the projection onto the surface below the visual perception threshold. Recently, a similar system based on the usage of depth sensors was presented. While they show how such an augmentation can be carried out with optically unaligned depth cameras and multiple projectors, the latency of the incorporated depth sensors makes it currently impractical for any fast and sudden motions. However, with more advanced and faster hardware, such limitations might be overcome.

Although the recent research results for high-quality non-rigid dynamic projections still lack the quality requirements of production standards, they show the future potential of such systems. Combining the advantages of the different methods with optimized algorithms and upcoming high-speed projection hardware will help to make such applications more widely usable in the near future.

3 High Speed Projection

High speed projection systems enabling a much higher frame rate than a normal video rate (e.g., 60 Hz) are required in low latency scenarios. It has been achieved using DLP projectors that represent an 8-bit pixel intensity by controlling a MEMS mirror flip sequence, whether it reflects a light from a light source to the objective lens or not, at thousands of frames per second. Research in the early stage focused on a real time shape measurement of a moving object by high speed spatial code projection or imperceptible code embedding in the context of optical communication. Recently, such high speed binary projection is applied to adaptive car head-lights which can avoid rain drop reflection and beaming to oncoming vehicle.

Currently, researchers focus more on high speed projection of meaningful images for humans in the context of dynamic projection mapping than binary pattern projection for machines. Dynamic projection mapping, in which a moving object is visually augmented by a projected imagery, was already described in Section 2, but in this section we will focus on it from a hardware perspective. Projection mapping applications generally require a precise alignment between a projected image and a physical surface. Even a small misalignment is salient, and thus, causes a significant degradation of the sense of immersion. This requirement becomes significantly more rigorous in dynamic projection mapping scenarios, in which a slight temporal delay of an even geometrically perfectly aligned projection causes a noticeable misalignment. For example, Ng et al. investigated the noticeable shortest latency for a touch panel interface. They showed that participants perceived a mis-alignment when the latency between touch input and the display of this visual feedback on the touch position was greater than 6.04 ms. This maps to a minimum desired frame rate of approx. 165 Hz and challenging latency requirements.

Recently two solutions have been presented to overcome this latency issue. First, the direction of an image from a normal projector is rapidly controlled using a dual-axis scanning mirror galvanometer system to project images onto a moving surface without perceivable delays. However, the frame rate of the projector is about 60 Hz and cannot interactively update the projected image content according to the movement of the surface without noticeable latency. Therefore, this method assumed that the perspective projection of the surface on the projector's image plane does not change while projecting, and consequently, the surface geometry is limited to simple shapes such as a sphere.

The second solution is to apply high-speed projectors that can display 8-bit images at several hundreds frames per second with low latencies. Watanabe et al. developed a projection device that has the ability to project 8-bit monochrome images at a frame rate of up to 1,000 Hz. To achieve the 1,000 Hz projection, the DMD's mirror flip pattern as well as temporally adapting LED intensities are used. Combined with a high speed camera (1,000 FPS) this projector is able to achieve a dynamic projection mapping onto rigid and deformable surfaces without noticeable misalignments. Kagami and Hashimoto achieved to "stick" a meaningful image onto a planar surface using a customized high-speed procams. Bermano et al. applied high speed procams to human face augmentation. For the latter, a commercially available 480 Hz projector was used. When handheld or wearable projectors are used, the projectors rather than target surfaces move. Regan and Miller proposed a technique to reduce motion blur artifacts in such situations using a high speed projector. Such systems have also been used in the fields of virtual and augmented reality other than projection mapping, where researchers have tried to minimize latency.

REFERENCES

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