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STAR – State of The Art Report

Recent Advances in Projection Mapping Algorithms, Hardware and Applications

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Abstract

This State-of-the-Art-Report covers the recent advances in research fields related to projection mapping applications. We summarize the novel enhancements to simplify the 3D geometric calibration task, which can now be reliably carried out either interactively or automatically using self-calibration methods. Furthermore, improvements regarding radiometric calibration and compensation as well as the neutralization of global illumination effects are summarized. We then introduce computational display approaches to overcome technical limitations of current projection hardware in terms of dynamic range, refresh rate, spatial resolution, depth-of-field, view dependency, and color space. These technologies contribute towards creating new application domains related to projection-based spatial augmentations. We summarize these emerging applications, and discuss new directions for industries.

CCS Concepts

•Computing methodologies → Computational photography; Mixed / augmented reality; •Hardware → Displays and imagers;

1. Introduction

During the last decade, projection mapping or spatial augmented reality (SAR) has been tremendously widespread over the world. The goal is to seamlessly merge physical and virtual worlds by superimposing computer generated graphics onto real surfaces. One of the biggest differentiator compared to other augmentation techniques is the capability of projection mapping to let many users directly experience the augmentation without wearing glasses or any other devices. Constant improvements in size, pricing, and brightness of projectors have allowed many people to develop their own projection mapping projects. They used a large variety of surfaces as projection targets: large buildings, cars, shoes, furniture, and even living creatures such as fish in an aquarium and human dancers. In the emerging application scenarios, there are strong demands for displaying desired appearances on non-planar, textured, and/or dynamically moving surfaces under environmental lightings. To meet the demands, researchers developed computational algorithms to project geometrically and photometrically correct images by applying *projector-camera systems (procams)*. Those procams use cameras to observe the projection onto the surface and to estimate how to adapt the projection image to display the desired augmentation.

Typically, projectors are designed and used to display images onto a planar, uniformly white, and static screen in a dark environment. Due to this fact, current projectors are not suitable for most projection mapping scenarios. Particularly, the dynamic range, frame-rate, latency, spatial resolution, depth-of-field (DOF), and the device's displayable color gamut limit their applicability. Furthermore, view-dependent images are not displayable. These technical limitations of the projector hardware make it difficult to display desired appearances in the wanted visual quality even when the computational algorithms are applied. Researchers have applied the emerging "computational display" approach, which is a joint design of display hardware, optics and computational algorithms to overcome the limitations [MWDG13].

This state-of-the-art-report summarizes the recent advances (in particular, the last 10 years) of projection mapping algorithms and hardware solutions to display desired appearances onto non-optimized real surfaces in an enhanced visual quality, and introduces emerging applications that apply these new technologies. The algorithms include robust camera-based auto-calibration tools for multi-projector systems, geometric correction for dynamic projection mapping, and radiometric compensation for textured surfaces (cf. Section 3). The hardware Section 4 introduces computational display solutions to overcome the mentioned technical limitations and to achieve high dynamic range, high speed, high resolution, wide DOF, view-dependency, and wide color gamut projections. The applications are summarized in Section 5.

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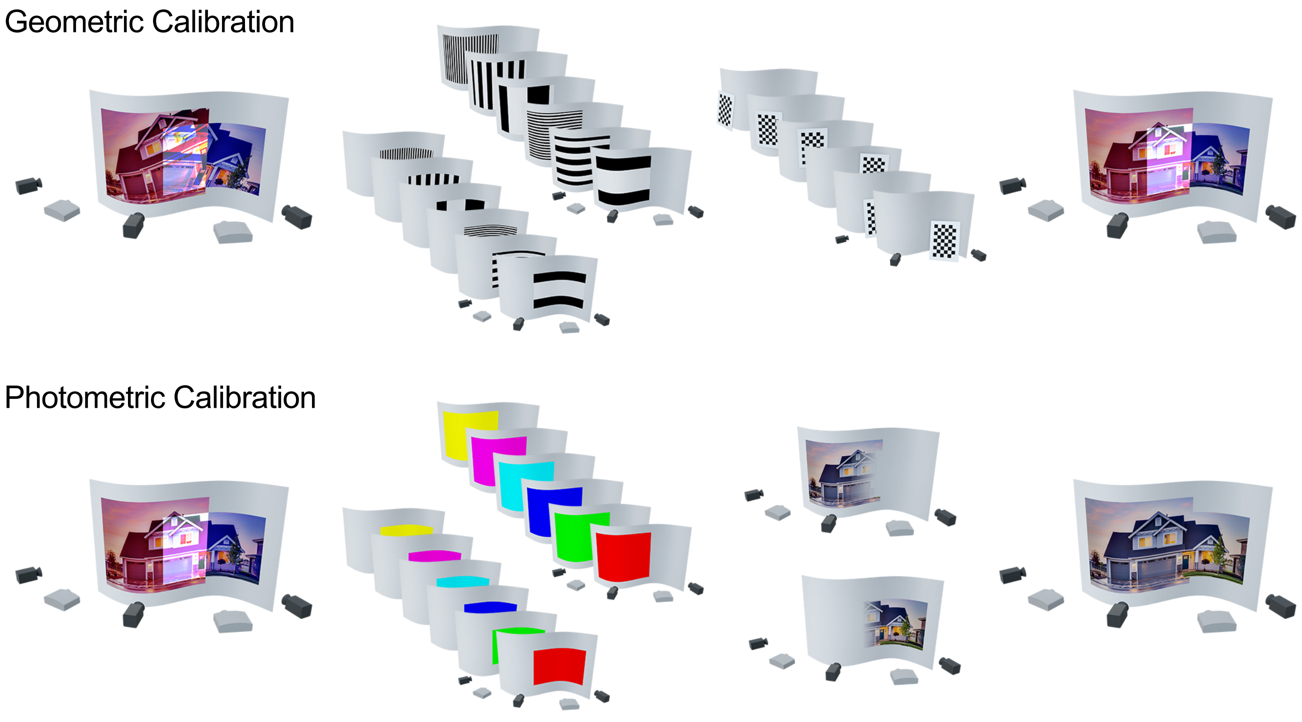

Figure 1: *Schematic overview of the fundamental calibration steps required by most procams applications. The process of geometric calibration is visualized exemplary on the top where cameras are used to capture projected structured light patterns, in this case gray codes, to generate projector to camera pixel correspondences. In combination with a multi-camera calibration, here, for example, based on planar checker boards, this is used to geometrically register the projectors to the surface and to enable the generation of a consistent projection onto a complex surface geometry as shown on the upper right. To also generate a colorimetrically consistent projection, additional color patterns are projected and acquired by cameras or other spectral sensors like colorimeters to photometrically calibrate the devices, and, in combination with information about the individual projector overlaps gathered from the geometric calibration, a completely consistent multi-projection system can be achieved as schematically shown in the lower right.*

This paper does not cover previous important technologies earlier than 2007. For interested readers which would like to get an even broader in-depth summary of that field, we recommend to refer to a book [BR05] and a state-of-the-art report [BIWG08]. Note that the paper does not cover related topics which are outside of the scope of the paper, which are (1) multi-projector calibration for wall displays and (2) high-quality shape measurement. Also note that we regard projection mapping, SAR, and projection-based AR as the same concept, and use the first term in the rest of the paper.

2. Projection Mapping in a Nutshell

Before we will give a summary over the current state of the art within the field of procams, we will present a short introduction to the fundamental tasks which need to be carried out in most projection mapping applications. As already stated in the introduction, projection mapping describes the usage of projectors for specific augmentations which should behave in a controlled desired manner. At a high level, applications can be classified into two categories: (1) ones with the desire to project geometrically undistorted content onto complex geometry; (2) ones which are able to flexibly control the color appearance of the projection, or a mixture of both.

To achieve such goals, several calibration steps have to be carried out which can be mainly classified into: (1) *geometric calibration* tasks dealing with the exact modeling of the shape of the projection surface as well as the internal and external parameters of the used projectors and cameras; (2) *photometric calibration* tasks which deal with the estimation of the internal color processing of the used input and output devices as well as the reflectance properties of the surfaces to project on.

Figure 1 schematically illustrates how these tasks can be carried out: The upper row illustrates a potential geometric calibration pipeline: cameras are used to capture a series of projected structured light patterns to generate pixel- or even sub-pixel-accurate mappings between projector and camera pixels. In combination with a geometric multi-camera calibration procedure, estimating their optical properties as well as global orientation with respect to each other, the surface geometry can be reconstructed and the projectors allows to be geometrically calibrated to generate a consistent projection image as shown in the upper right. To additionally ensure that a photometric uniformity is also achieved, several further color and intensity patterns are projected and analyzed to estimate the device's internal color processing as well as the light modulation on the surface. In combination with the geometric information, the projector overlaps are smoothly blended to finally generate a photometrically homogeneous projected image (lower row).

3. Algorithms

The following section focuses on current procams related research based on novel algorithmic methods. Since the hardware, i.e., the combination of cameras, projectors and other specialized devices limit the algorithmic applications, the majority of the ones described below are adaptations and incremental improvements of earlier methods or are derived from neighboring fields of visual computing. New applications which have been realized by making use of new hardware devices will be discussed later in the Hardware Section 4.

We mainly subdivide the algorithms section into methods related to the *geometric calibration* of procams which, for a majority of applications, is a crucial requirement. This is the task to estimate the three-dimensional properties of the devices as well as their relationship with respect to each other, as well as to the surface in contrast to a projector-camera pixel correspondence estimation and mapping into a two-dimensional space, which we call *geometric registration*. Secondly, the upcoming research field of *dynamic projection mapping* will be discussed and as a third area we summarize research for calibrating and compensating the *radiometric properties* of procams. Those will be classified into methods for per-pixel diffuse surface reflectance compensation, as well as into ones for the compensation of global effects such as inter-reflections and dynamic closed-loop systems.

3.1. Geometric Calibration of Projector-Camera Systems

Since projection mapping has been becoming more and more popular for professional applications at large scale venues such as events, marketing, and theme park attractions, tools were developed to ease the calibration and maintenance of such installations to guarantee a quick, efficient setup with adequate reliability. Therefore, several companies developed toolboxes for projection mapping applications, such as Microsoft with the freely available Kinect based RoomAliveToolkit [JSM*14]. Also several projection hardware and software companies offer commercial applications to simplify projection mapping installations [sca, chr, vio, gre, mxw]. The Walt Disney Company develops a procams toolkit for theme park attractions simplifying deployment by an automated calibration procedure and ensuring a reliable long-term maintenance process to widen the creative potential of such systems within the mentioned context [MvBG*12].

3.1.1. Semi-Automatic Procams Calibration Methods

Most methods to calibrate projectors usually start with one or multiple cameras, which are initially either pre-calibrated or not calibrated at all. Calibrating the intrinsics of cameras can be carried out in various ways, the most widely used ones involve multiple captured images of a planar marker board of unknown orientation, often with a checkerboard pattern, to estimate the focal length, principal point, and specific amount of parameters to model the lens distortion. The most commonly used method to apply this calibration is presented by Zhang et al. [Zha99], which is also widely used as the baseline to compare other calibration methods. Since the accuracy of such methods strongly depends on the number of samples and marker orientations within the various captured images, in Richardson et al. [RSO13], efforts were made to actively assist users in selecting the most useful poses to generate an accurate calibration result: The authors propose an iterative method to estimate the most suitable marker orientation for the next capture from the current calibration results, which could be shown to improve the calibration accuracy. The same checkerboard method can also be used to calibrate the relative orientation of the cameras, i.e., the extrinsic properties, by presenting the same patterns in different camera views.

Having at least two calibrated cameras, a projector calibration can be carried out using structured light patterns to generate correspondences between all cameras and projectors. Since the cameras are already calibrated, the correspondences can be used to triangulate a point cloud of the surface and then use this information to register the projectors to the surface by using the 3D-to-2D point-to-pixel correspondences to estimate the projection matrix using the Direct Linear Transform (DLT) approach and an additional non-linear optimization of the decomposed intrinsics and extrinsic calibration components as, e.g. explained in [HZ04].

To avoid the requirement of using multiple calibrated cameras for projector calibration, methods were proposed to calibrate the projector via planar surfaces in an equivalent fashion to the aforementioned camera calibration, but this time, by treating the projector as an inverse of a camera and using structured light patterns to estimate with a single camera, where each projector pixel is seen on a planar surface [ORH08, DAS*14, MT12, LHG11]. An easy to use checkerboard-based procams calibration method and source code has been introduced [AO09]. It calibrates the projector via planar surfaces by treating the projector as an inverse of a camera and using structured light patterns to estimate with a single camera where each projector pixel is located on the plane. Recently, this process was simplified by using self-identifying projected blob patterns, which can also be robustly detected when projected onto planes which are placed significantly out of the focus plane of the projector [YNM16]. Related plane-based methods also nicely summarizes further-related methods and differences between them [DRS12].

If the geometry of the projection surface is known, manual correspondences can also be generated without using a camera by marking corresponding surface features in the projection and mapping them to the according position of a known 3D geometrical shape [CMT10]. However, besides the fact that this is often not available, this process is cumbersome and error prone due to the required manual interaction; thus is not suitable for a reliable long-term deployment.

3.1.2. Self-Calibration Methods

Instead of using plane-based calibration methods based on homographies for calibration estimation, several semi- and full auto-calibration techniques for procams have been presented. One of the first methods to fully automatically calibrate a generic projector-camera pair without using a planar surface, for example, has been proposed by Yamazaki et al. [YMK11]. They propose an algorithm based on the decomposition of the radial fundamental matrix into intrinsic and extrinsic parameters, which requires a close-to-pixel accurate prior for the principal point, i.e., the location of the optical axis on the projector's image plane. This is hard to achieve in real-world situations, since in most projectors the principal point is usually not located close to the center of the image plane but shifted on the y-axis due to the lens shift optics. Sajadi and colleagues present a system which enables the calibration of multiple cameras and projectors, assuming that the cameras all share the same focal length and contain no distortion parameters, which might not lead to a sufficiently-accurate calibration depending on the used lenses [STRM15].

Garcia et al. proposed a method to calibrate a specific multi-camera-projector-system in which sensors face each other and share a common viewpoint using translucent planar sheets placed at a series of varying orientations to generate planar pixel correspondences between all devices [GZ13]. Using this information, the standard method presented by Zhang [Zha99], with an additional sparse bundle adjustment (SBA) step [TMHF00], is used to calibrate the devices. Although the approach is able to accurately calibrate multi-projector setups, it is limited for a specific configuration and, thus, cannot handle the desired variety of complex setups. Recently, a method was proposed by Garrido-Jurado et al. [GJnSM-CiJ16], which offers a flexible self-calibration method. However, it also has several limitations. The most important one is the fact that the it is assumed that the intrinsics of the devices are already known beforehand, which is usually not the case, but part of the desired calibration process, especially since, for practical reasons, zoom and focus are often readjusted for each particular setup. Because of that limitation, their strategy to insert new devices focuses solely on the number of available correspondences and how to optimize the device integration strategy using a mixed integer linear programming approach. Although their method showed convincing results for a specific setup, the requirements of having the intrinsics pre-calibrated, no direct outlier treatment, and a relatively simple integration strategy when compared to, for example, the strategy proposed by Snavely et al. makes it less flexible for generic usage [SSS06].

Another recent method presented by Li et al. uses priors for the principal points as well as for the focal lengths [LSD*17]. While the principal point can be roughly estimated to be in the center for cameras, this is, as already mentioned, usually not the case for projectors. To estimate them the authors propose a method that requires the zoom level of the projector to be changed. Initially not all projectors have different zoom levels and changing the zoom usually has to be done manually which makes the approach impractical. Also the required rough estimate of object size and distance for focal length priors makes it less applicable. A metric procams self-calibration method is presented which makes use of an existing, known 3D geometrical model of the projection surface [RNK*15]. Using this information plus priors about the focal length, a projection device can be calibrated into a coordinate frame with respect to the model even in the desired scale. However, all of these methods require specific priors, i.e., information about the intrinsic device properties, or manual interaction and thus are not generically applicable, yet.

A generic method was presented which uses at least two or more cameras to apply a full self-calibration without the requirement of any prior [WG17]. To achieve that, an adaptive and outlier insensitive integration scheme was applied to achieve the required robustness of the fundamental matrix estimation and the consecutive device calibration and surface reconstruction. This is crucial since, especially outside of lab environments, the structured light process often might lead to a certain amount of false correspondences which significantly degrade the self-calibration accuracy if not detected and removed during the calibration process.

3.2. 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. The interested reader is referred to a prior work [NLW*12] for an experiment and discussion about the sensitivity of human visual perception with respect to visual lagging.

Below we will summarize the recent developments firstly by listing work focused on rigid dynamic surfaces and secondly for non-rigid augmentations. Figures 2 and 3 respectively show examples of rigid and non-rigid dynamic projection mapping technologies, which are introduced in the following subsections.

3.2.1. Rigid Dynamic Projection

Methods for the augmentation of rigid dynamic objects do not require a full dense online surface reconstruction, but only a pose

Figure 2: *This figure summarizes examples of rigid dynamic projection mapping: The top row shows three augmentation results of a rigid dynamic multi-projector mapping onto a uniform gray face statue [SCT*15]. In the bottom left, a dynamic projection mapping onto an animatronic head is shown using multiple projectors which are compensating for sub-surface scattering as well as image degradation artifacts from defocus [BBG*13]. The upper three images show different facial expressions. The small images always show the animatronic head under uniform white illumination as well as the gray shaded rendered geometry which was used as input for a registered spatially varying lighting projection shown in the enlarged photographs. Below, several close-ups of the augmented animatronic head are shown. In the bottom right figure a marker-based dynamic projection mapping is shown where the perception of the markers is reduced by visually diminishing them using a radiometric compensation approach (cf. lower two photographs) [AIS15, AIS18].*

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 (cf. Section 3.3) to visually cancel the markers [AIS15, AIS18] (An example is shown in Figure 2). Other researchers replace the markers with tiny photosensors to measure the scanning timing of a projected beam from a laser projector [KIS17]. 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 [RKK14]: 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 [Zha94] 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 [SCT*15] (cf. Figure 2). A related method using an infrared camera was also presented by Hashimoto et al. [HKK17]. A method for optimal projector assignment for dynamically moving rigid objects using the normal vector information was proposed [LWF11]. 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 [BBG*13] (cf. Figure 2). 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 [SH13], Block-Matching [HKAJ*14] has been used to predict the unknown motion of a human hand. Leveraging a 1,000 Hz high speed procams (cf. Section 4.2), a visual marker-based method achieves a very low latency registration [WKi17]. 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).

3.2.2. Non-Rigid Dynamic Projection

A solution for dynamic projection mapping onto a deformable object is described by Punpongsanon et al. [PIS15a]: 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 (cf. Figure 3, upper right). A high-speed camera is used to robustly track dot cluster markers drawn by the same invisible inks [NWI15]. Alternatively, retro-reflective markers are used to measure the surface deformation in the word of Fujimoto et al. [FST*14]. 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. [NWI17] (cf. Figure 3, lower right).

A system to dynamically augment human faces using projection was presented by Bermano et al. [BBIG17]. 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 [SLS*17]. 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. Please refer to the left panel in Figure 3 for application examples of the last two discussed methods.

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 [DYNa] will help to make such applications more widely usable in the near future.

3.3. Radiometrical Control of Projector-Camera Systems

This section discusses the problem of accurately measuring, controlling, and compensating the light which is emitted by the projectors and reflected from the surface. Although the basic linear models for describing the local color transformation and applying a radiometric compensated projection have been developed already for a long time,† several recent papers present enhancements to overcome the limitation of these models, especially with respect to computational complexity, color reproduction accuracy and discretization error minimization. Figure 4 shows several examples of some of the radiometric compensation techniques introduced in the following.

3.3.1. Local Per-Pixel Radiometric Compensation

The basic radiometric compensation methods modeled the light modulation between a camera and a projector as a linear matrix multiplication. This color-mixing matrix based approach was proposed by Nayar et al. and Yoshida et al. [NPGB03, YHS03]. More recently, this model has been further analyzed and adapted to simplify the computational steps by separating the spatially-varying effects from the constant color-mixing property between the used camera and projector in the work of Chen et al. [CYXL08].

When projecting onto dark or strongly saturated surface pigments, it is desirable to avoid visually disturbing compensation errors resulting from the limited color gamut of the projector. Several methods automatically adjust the target colors outside of the displayable gamut to mitigate such artifacts [MJK11, LAS*11]. Menk and Koch proposed to use physically based computation based on spectral measurements in combination with HDR imaging to generate more accurate projection based augmentations [MK10]. The approach was further extended by applying a 3D lookup table (LUT) to describe the color model of the projector [MK13].

A more accurate color reproduction, especially when applied to single-chip DMD-based projectors using multi-primary color

† Please refer to a state-of-the-art report [BIWG08] for details

Figure 3: *Examples of non-rigid dynamic projection mapping. Solutions for fully dynamic human face augmentations have been presented by multiple research groups as shown on the left hand side. The images shown on the top are results of the work of Bermano et al. [BBIG17] in which a high-speed procams is used to warp and texture a 2D facial mesh for low-latency real-time augmentations simulating varying lighting conditions, texture and expressions. The augmentations shown in the bottom row are generated using a multi-projection system [SLS*17]) in which the non-rigid face deformation is measured using depth sensors and projected back by multiple devices. On the right hand side, dynamic augmentations onto other deformable surfaces are shown: On the top, an augmentation of a deformable surface is shown as presented by Punpongsanon et al. [PIS15a], on the bottom right, a real-time augmentation onto non-rigid paper and a t-shirt as described by Narita et al. [NWI17] is shown.*

wheels and an internal non-linear color processing is achieved using a non-linear thin-plate-spline interpolation [Gru13]. While this requires a significantly more complex interpolation model based on radial basis functions (RBF) to be calculated and solved, it could be shown that the resulting improvement in compensation quality is applicable for real-time processing when implemented on the GPU. Grundhöfer and Iwai extended this approach and showed a method to reduce perceived artifacts at strong texture edges resulting from the unavoidable fact that projector pixels might hit multiple surface pigments with varying reflectance properties at texture edges, leading to artifacts due to overcompensation [GI15]. Mihara et al. also presented a solution for the latter, where a precise compensation is achieved by considering the potentially spatially-varying reflectance observed by a high-resolution camera in the area of each projected pixel [MIS14].

Since the placement of the available projectors in combination with the geometrical shape of the object to augment has a significant impact on the visual quality of the compensated projection, approaches were presented to automatically calculate an optimal projector placement to achieve the best compensation result [LAM10]. Other methods focused on optimal projector placement in terms of pixel coverage and intensity distribution [LXZ*15].

3.3.2. Inter-reflection Compensation

The methods presented in the last section are only able to improve the image quality locally since the compensation is carried out independently for each pixel or, in some cases, incorporating locally neighboring pixels, i.e., considering not more than the influence described by a narrow local light transport. However, these methods are not able to handle and neutralize any kind of global illumination effect. Even when using only Lambertian surfaces, diffuse inter-

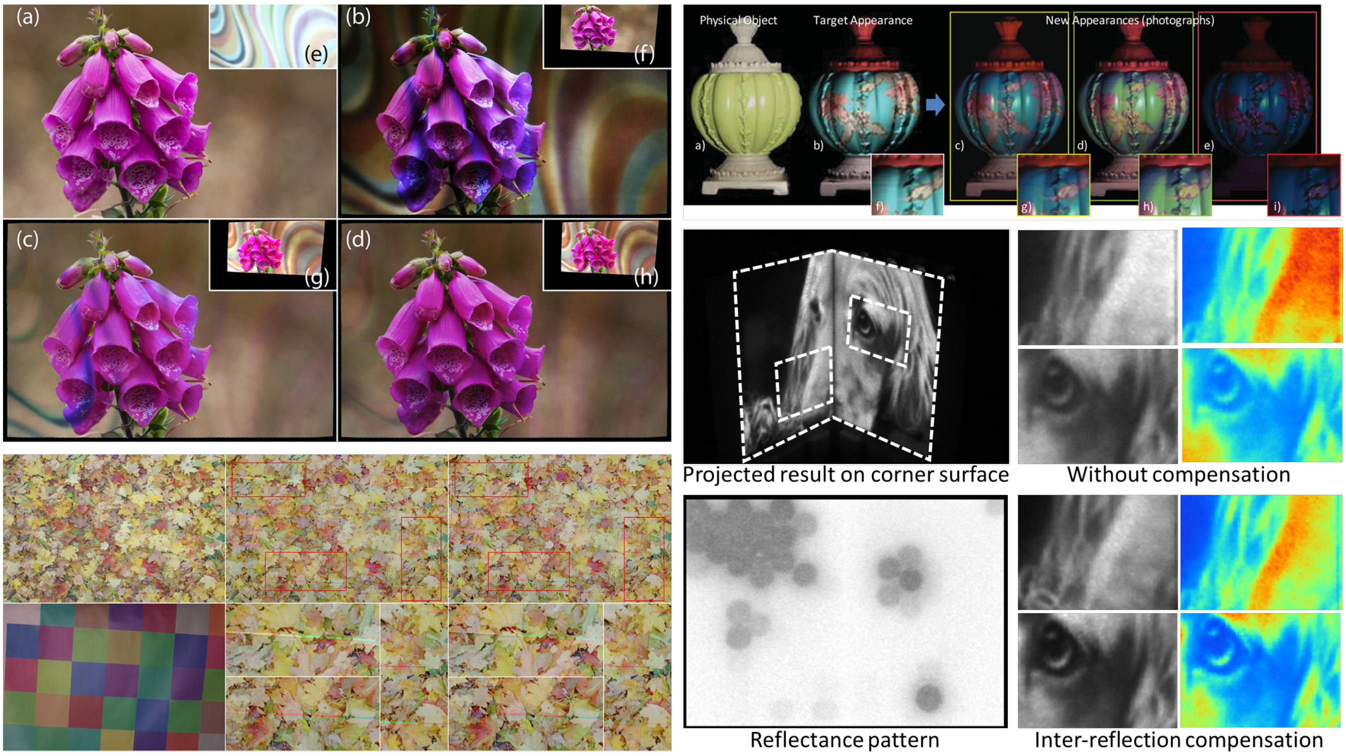

Figure 4: *Examples of radiometric compensation methods: Upper left: Non-linear per-pixel photometric compensation without (c) and with (d) local content adaptation [Gru13]. Lower left: Photometric compensation with error minimization to reduce the perception of color artifacts in areas of significant reflectance change [GI15]. The photograph of the leaves is projected using photometric compensation onto the highly saturated color patches. Even slight misregistrations lead to color artifacts at the edges (middle column, close-ups shown in the bottom). By considering the local surface reflectance and the potential projector drift, the compensation can be adjusted to diminish these artifacts (right column). Upper right: High-quality projection-based appearance editing as proposed by Law et al. [LAS*11]. Lower right: Compensation of indirect diffuse scattering by active and spatially varying reflectance modulation using photochromic inks illuminated by an array of ultraviolet LEDs [TIS16].*

reflections will happen at any concavity. This unwanted scattering of light degrades the image quality by a reduction of contrast and might lead to undesired color-bleeding.

Compensating the influence of such inter-reflections was initially presented by Bimber et al., where a global illumination calculation was carried out to estimate the amount of inter-reflections by subdividing the surface into patches [BGZ*06]. Since the compensation depends on the projected image content, the method was optimized for real-time processing to enable the compensation within interactive applications, such as immersive virtual environments. Such inverse radiosity methods were then further refined by several groups [SYC10, SCCN11, NPB*12]. Most of these methods were also able to compute a compensation image in real-time using GPU-based parallel processing. A more recent publication solving the same problem in real-time for multiple projectors in a dynamic environment has been presented by Siegl et al. [SCSB17]. Habe et al. presented an inter-reflection compensation algorithm specifically designed for dome-shaped projection surfaces [HSM07]. Unfortunately, this approach is accomplished by reducing the overall projected intensity by a certain, spatially constant factor which contradicts with the natural goal of maximizing contrast. Within a more general solution presented by Wetzstein and Bimber [WB07], inter-reflection artifacts were compensated by inverting the light transport matrix between a projector and camera.

Although being algorithmically different, the inverse radiosity methods all share the same principle of reducing illumination in areas where strong inter-reflections occur which leads to a lower overall intensity. Another approach to overcome this issue by dynamically modulating the local surface reflectance was presented, in which the reflectance of a projection surface is modulated to achieve a better inter-reflection compensation and to improve perceived contrast [TIS16]. This is achieved by using a UV-reactive photochromic surface material which, when illuminated by high-power ultraviolet radiation, changes its reflection properties from bright to dark (cf. Figure 4, lower right).

Besides inter-reflection compensation, a model-based technique for radiometric compensation was presented, where the reflected spectral distribution of the ambient light is measured and the data is used to compute the correct compensation intensities to accurately approximate the desired color when projecting onto the surface [MK10].

3.3.3. Closed-loop Radiometric Compensation

While the research summarized in Section 3.2 focuses on a geometrically accurate projection onto rigid and non-rigid dynamic surfaces, other approaches are targeted more onto the appearance control of moving objects by applying closed-loop radiometric compensation models using a coaxial procams as proposed by Amano and Kato [AK10b]. Optically aligning a projector and a camera is a non-trivial task and quite cumbersome since the alignment has to be managed in six degrees of freedom. To ease the registration, a simple, but efficient way to achieve a satisfactory optical calibration of the coaxial procams is given, where a spatial grid pattern is projected onto a differently shaped grid surface such that the alignment accuracy can be directly estimated by observing the camera while moving the latter [Ama14]. The same principle of a coaxial procams is used to visually manipulate material appearance [Ama13], microscopic specimens [BKA*11], shading illusions [Ama12], and context aware illuminations [WFF*10]. The same idea was extended to multiple coaxial procams which were used to augment a 3D object [ASUK14]. The convergence of such a radiometric compensation approaches from multiple projectors is theoretically proven by Tsukamoto et al. [TIK15].

3.4. Summary

As discussed in this section, the development of new, optimized algorithms for procams is still an ongoing and active field of research. We classified the ongoing research into three main categories which seemed to be most relevant for high-quality projection mapping applications:

- Geometric calibration and, in particular, self-calibration methods (Section 3.1) were recently presented by various groups. Most of the work builds upon and adapts ongoing computer vision research on multi-camera calibration. Since the calibration of projectors generates some additional constraints, but also helpful priors, there is still room for further improvement.
- Dynamic projection mapping is becoming a more and more popular field of research (Section 3.2). Especially with the current development of high-speed projectors and the availability of fast cameras, we might just experience be the beginning of a growing area of real-time augmentation systems. We need further research to realize augmentations for more complex dynamic surfaces.
- Radiometrical control of projector-camera systems in several areas is summarized in Section 3.3. It is also profiting from new hardware devices allowing to more accurately reproduce and thus control colors, in the spatial as well as in the spectral domain. It is also a challenging issue to control the colors of non-lambertian surfaces.

As already noticed, many physical limitations of projectors cannot be overcome by algorithms alone, but also require modifications and research on the hardware side. Recent new projection hardware developments and the according computations will be summarized in the following section.

4. Hardware

Conventional projection devices and their optical system are generally designed to maximize the projected image quality for a flat, non-textured, and perfectly Lambertian surface. The software-based solutions described in Section 3.3 have been proposed to improve the visual quality when projecting onto imperfect surfaces, but algorithmically this is only possible up to a limited extent. Such technical limitations stemming from the projector hardware were already pointed out in a state-of-the-art report presented in 2007 [BIWG08]. The following section describes technologies that go beyond algorithmic improvements to further improve the projected image quality for arbitrary surfaces by applying an emerging approach, *Computational Projection Displays*—a joint design of display hardware, optics and computational algorithms [MWDG13].

4.1. High Dynamic Range Projection

The dynamic range or contrast of a projection display is defined as the ratio of the maximum to minimum luminance. The range of luminance values in the real world is extremely wide ($>$ 1,000,000), from an outdoor scene in sunshine to an indoor scene under a candle light. Consequently, a high dynamic range (HDR) representation would be required to realistically render and display both natural and computer generated images. However, current projectors, except for laser-based devices, can support only a significantly limited dynamic range; i.e., a simultaneous in-scene contrast is typically limited to the range of between 1,000:1 and 6,000:1 [DBK*15]. Note that this section discusses the simultaneous dynamic range that is achieved without additional mechanical adjustments, such as auto-iris aperture control, which globally brightens or darkens all the pixels in a projection image and does not change the contrast within a single image. Several solutions have been presented to overcome the contrast limitations. They can mainly be subdivided into methods trying to achieve that goal by reducing the black-level and hardware which locally amplifies the amount of photons. We will discuss them in the following paragraphs.

HDR projection has been achieved by applying the double modulation principle, by which the emission of a light source is spatially modulated twice at cascaded light blocking spatial light modulators (SLMs), e.g., a digital micromirror device (DMD) or a liquid christal display (LCD), to reduce the luminance of dark pixels (or black level while maintaining those of bright pixels. Researchers proposed several double modulation methods so far such as applying two LCD panels, and these successfully increased the dynamic range of a projected image by significantly lowering the black level luminance which is perceived when displaying zero intensity values (for more details, see a state-of-the-art report [BIWG08]). Recent works applied dual LCoS (Liquid crystal on silicon) designs [HWR14, HLR*14]. However, these methods do not increase the peak luminance at the same time, which is one of the essential perceptual attributes of realistic image appearance.

Recently, a novel, energy efficient, double modulation method was proposed, where the first modulator unevenly reallocates the light from the light source onto the second modulator such that light energy gathers on bright parts of a projection image while it scatters on dark parts without decreasing the total light energy.

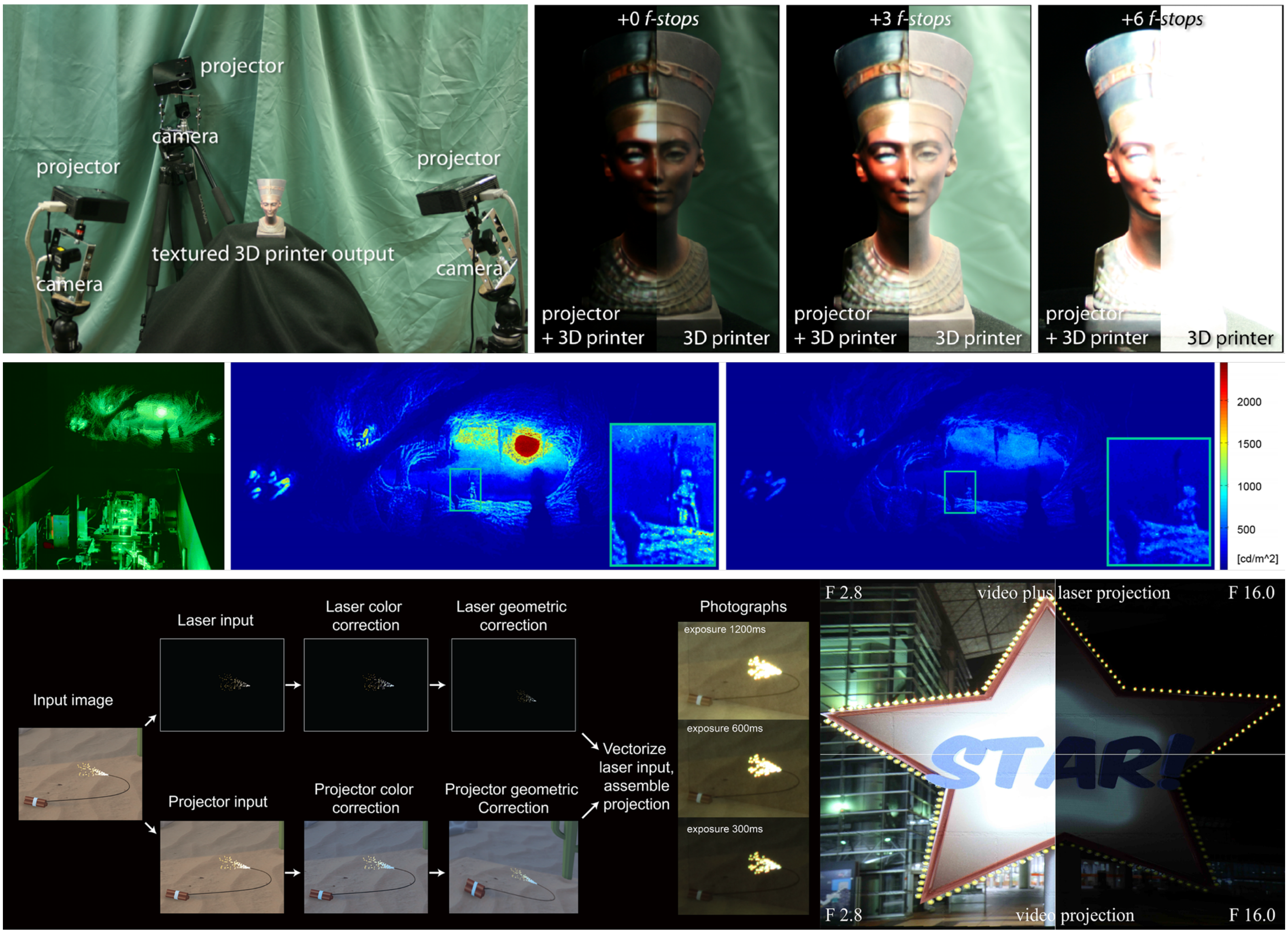

Figure 5: *Examples of HDR projections. Top Row: 3D HDR representation by modulating the surface reflectance using a full color 3D printer and combining it with registered, spatially modulated projected light [SIS11]. Middle Row: HDR projection systems based on dynamic spatially varying light reallocation [DBK*14]. Bottom row: Superimposing registered video projectors with galvanoscopic laser projection devices enable the generation of local HDR projection effects [WG16, PWG17]. The physical limitations of the galvanoscopic mirror movement such as maximum speed and inertia are the main limiting factors of the latter.*

The second modulator then forms the final projection image. Two types of light modulators have been applied as the light reallocator. The first one is an analogue mirror array (AMA) that consists of two-dimensionally aligned pan-tilt MEMS mirrors [HSHF10]. Since each mirror of an AMA independently controls the direction of light, energy from the light source is spatially reallocated onto the DMD used as the second light modulator. The second configuration uses a phase modulator or freeform lensing approach [DBK*14,DBK*15,DGH16]. Here the original light energy is reallocated based on a dynamic goal-based caustics principle [PJJ*11] that gathers and disperses light using spatially-varying diffraction patterns. Therefore an LCoS was applied as a phase modulator in [DGH16]. The big advantage of the latter, light-reallocating double modulation methods is the significantly limited light loss and the extremly high local intensities which can be generated by focusing all available light onto a single pixel region. However, this also generates difficulties on the content generation side since with that approach, a specific light budget needs to be intelligently distributed spatially as well as temporally to generate a consistent visual impression without flickering. Sample prototypes are shown in the center of Figure 5.

Even when an ideal projector with infinite dynamic range is applied, environmental light and/or global illumination effects such as inter-reflection increases the reflected black level which consequently decreases the dynamic range of the projection. In particular, it is natural to assume that many projection mapping applications are run with a small amount of environment light contribution and non-flat, concave surfaces might be used as projection targets. Therefore, increasing the dynamic range of a projector is not sufficient, but the whole projection system including the surface must be optimized. To this end, researchers have proposed to spatially modulate the reflectance pattern of a projection surface to suppress the

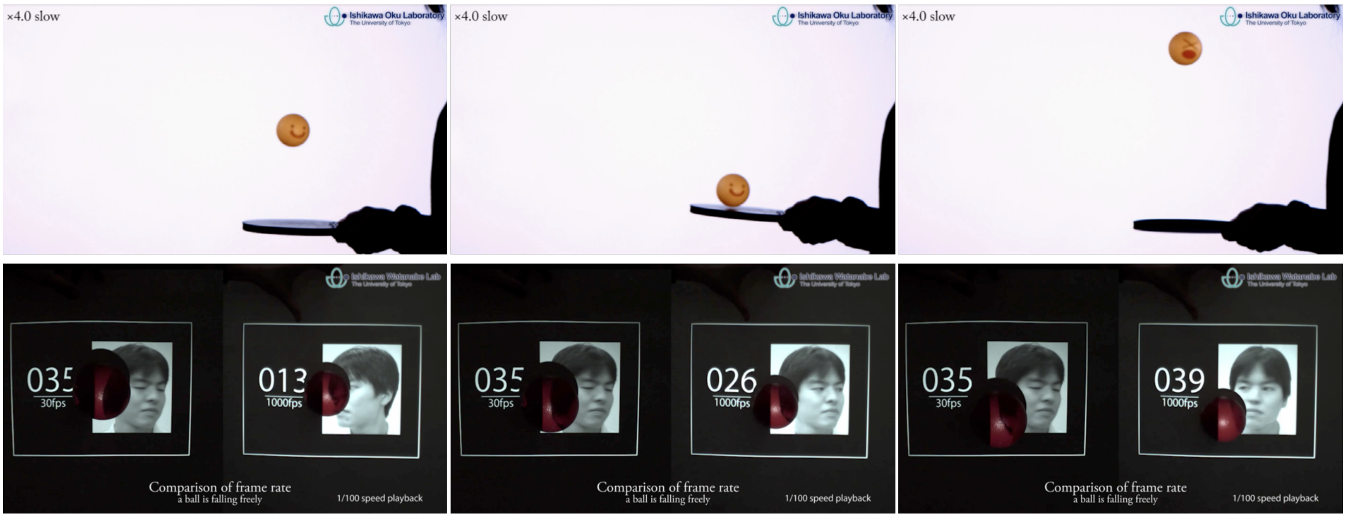

Figure 6: *Examples of high-speed projection devices. Top Row: High-speed low latency projection system combining a normal projector and a dual-axis scanning mirror galvanometer system enabling the augmentation of the ping pong ball without any perceived lagging [OOI12, LUM]. Bottom Row: In this comparison between a normal 30 Hz and a 1,000 Hz projector the effect of the limited image refresh rate is demonstrated by these three images taken in rapid succession: The low frame rate projector still displays the same image while the red ball falls down [WNT*15, DYNb].*

elevation of black level [BI08, SIS11, JSB*15, ITHS14] (cf. Figure 5, upper row). More specifically, the luminance of a projected light is theoretically computed as the multiplication of the reflectance of a surface and the incident light illuminance. Therefore, it is possible to avoid undesirable black level elevation by decreasing the reflectance at a place where dark image should be displayed.

Bimber and Iwai proposed to use printed media including an e-ink display for the reflectance modulation [BI08]. This was also extended to static 3D surfaces by applying a full-color 3D printer [SIS11]. Because these methods applied static or almost static reflection media, dynamic image contents such as movies are not suitable. Jones et al. proposed to optimize the surface reflectance pattern to display a short periodic movie sequence in HDR [JSB*15]. A dynamic modulation of the reflectance pattern was also investigated by Iwai et al. who proposed to cover the projection surface with a photochromic material such that the surface reflectance can be spatiotemporally controlled by applying UV illumination [ITHS14].

Another alternative approach to generate local HDR effects can be achieved using galvanoscopic laser projectors. However, since they require physical mirror movement, the amount of displayable content without the perception of flickering is significantly limited. A method is presented to optimize the spatio-temporal scanning order and speed of such laser-projected point sequences to increase the number of displayable points [WG16]. The same hardware was used to also generate a photometrically calibrated and consistent combined video-laser-projector system [PWG17] as shown in the bottom of Figure 5.

4.2. 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 (for more details, see a state-of-the-art report [BIWG08]). Recently, such high speed binary projection is applied to adaptive car headlights which can avoid rain drop reflection and beaming to oncoming vehicle [TNC*14].

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 3.2, 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 [NLW*12]. They showed that participants perceived a misalignment 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 (cf. Figure 6). 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 [OOI12, SOI15]. 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 [WNT*15]. 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 [NWI15, NWI17, WKi17]. Kagami and Hashimoto achieved to "stick" a meaningful image onto a planar surface using a customized high-speed procams [KH15]. Bermano et al. applied high speed procams to human face augmentation [BBIG17] (see Section 3.2). 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 [RM17]. 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 [LBS*16, ZWL*14].

4.3. High Resolution Projection

It is highly demanded to realize a high resolution projection since, due to the high spatial resolution of the human eye, an apparent projected pixel quickly is recognized as a rectangular shape in projection mapping applications where the viewing distance is sometimes very short. There are two main approaches to accomplish this goal: (1) using multiple projectors to generate a higher resolution, or (2) realizing this task with a single projector. Figure 7 shows examples of high resolution projection systems.

In a multi-projector approach, a traditional method is to tile multiple projected images. Several techniques have been proposed to make overlapping areas and differences of luminance and chrominance visually imperceptible among multiple overlapping projectors. We recommend readers interested in these techniques to refer to a book [MB07]for more details. Considering the spatially-varying property of the retinal acuity of the human vision, another tiling method applies two projectors: one for the sharp central vision, and the other for the peripheral vision [IKS15]. The former is a narrow but high resolution projector whose projected area is moved by a pan-tilt mirror within the projected area of the latter projector that has a wider projection area but lower resolution. Projection-based super resolution approaches have also been investigated by several groups [DVC09, AYL*12, OWD09]. Projected images are superimposed onto each other in such a way that the images are slightly shifted with respect to each other by offsets smaller than one pixel width. Optimization techniques such as a least squares method are applied to compute each projected image to achieve a high resolution target. Because of the subpixel offsets, the super resolution approach can display significantly higher spatial resolution than a single projector. However, due to the additive nature of projected images (i.e., there is no negative light), there is a theoretical limit in the achievable resolution [OWD09] and the required highly accurate calibration is cumbersome and hard to maintain.

In contrast to the latter approach, a single-projection approach applies multiple spatial light modulators or special optics within a single projector to achieve higher resolution than a normal projector. Wobulation is one of the pioneering techniques, which shifts the DMD half a pixel at successive frames so that two slightly shifted images are overlapped [AU05]. Because the frame rate of the projector is 120 Hz, two overlapped images are not perceived as separate images. This technique can be regarded as a super resolution approach in a temporal domain and is now being used as a standard method for consumer-grade 4K projection systems [TIDb, TIDa, opt].

Another super resolution approach combines two cascaded spatial light modulators that are slightly shifted to achieve a high resolution image projection [HWR14, HLR*14]. While the so-called *wobulation* is an additive super resolution technique, this cascaded display technique is a multiplicative super resolution approach and achieves theoretically significantly higher resolution. Special optical elements have been also applied to realize high resolution projections. For example, the "half a pixel offset" can be optically achieved using shifting lenses [SQLI*13]. As another method, optical pixel sharing technique enhances the resolution using smaller pixels at specific regions of interest like edges [SGM12]. A target high resolution image is first decomposed into a high resolution but sparse edge image, and a complementary lower resolution non-edge image. These image pairs are then projected in a time sequential manner at 120 Hz to create an edge-enhanced image, i.e., an image where the pixel density is not uniform but changes spatially.

4.4. Increasing Focal Depth

Projectors are inherently designed with a large aperture to minimize the loss of light emitted from the light source. However, this optical design leads to a shallow depth of focus (DOF). Consequently, an image projected on a surface with large depth variance can become blurred quickly. Therefore, extending DOF of projectors is highly demanding issue especially in dynamic projection mapping applications where projection objects and/or projectors are moving in large spaces. Previous techniques fall into two categories: single-projector and multi-projector approaches.

Single-projector approaches digitally sharpen original images before projection so that an optically defocused projection closely

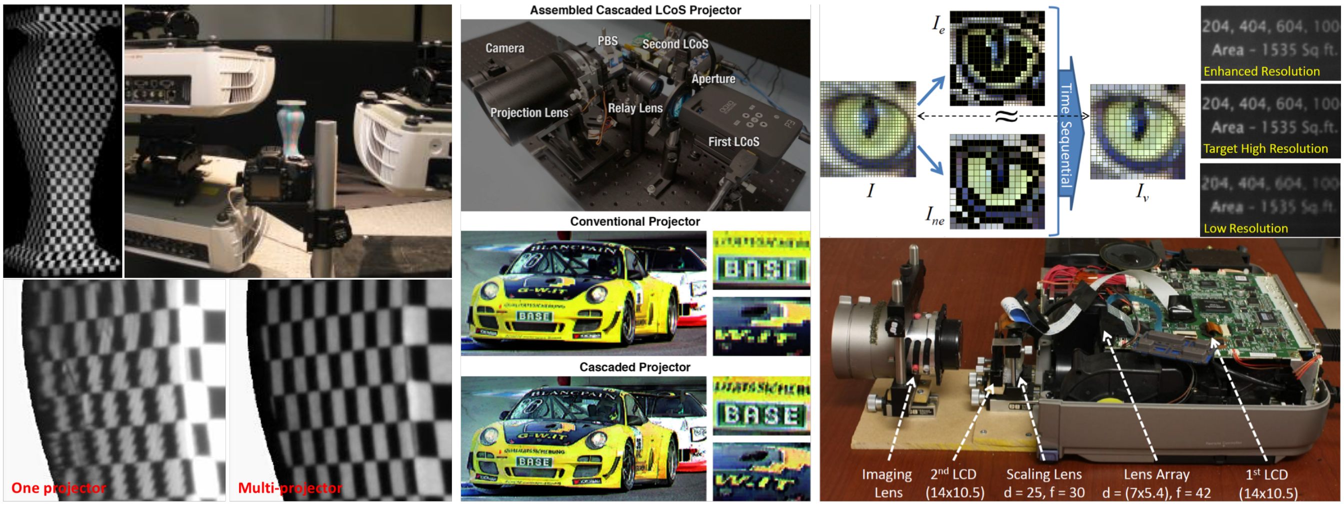

Figure 7: *Examples of high resolution projection systems. Left: Super resolution projection by overlapping multiple projectors [AYL*12]. Middle: A custom high resolution projector with two cascaded spatial light modulators laterally shifted each other regarding the optical axis [HLR*14]. Right: Optical pixel sharing technique where a high resolution edge image and complementary lower resolution image are displayed in a time sequential manner at a high frame rate (i.e., 120 Hz) [SGM12].*

approximates the original (i.e., unblurred) image. Defocus blur of a projected image is explained mathematically as the convolution of a PSF (point spread function) and the original image. If the PSF of a projector on an object's surface is estimated correctly, a defocus-free image can be displayed by digitally correcting the original image using a deconvolution method, such as the Wiener filter [BSC06]. Zhang and Nayar formulated image correction as a constrained optimization problem [ZN06]. However, as summarized in a state-of-the-art report [BIWG08], such techniques suffer from the loss of high frequency components because PSFs of normal projectors are generally low pass filters. In the last 10 years, new optical designs have been introduced to enhance the performance of extending the DOF of a projector. For example, researchers apply coded apertures that have two-dimensional complex patterns instead of an ordinary circular aperture to make the PSFs more broadband [GWGB10, MSD*13]. Another strategy is to apply a focus tunable lens (FTL) to sweep the focusing distance through the scene to make the PSF invariant to scene depths [IMS15] (Figure 8).

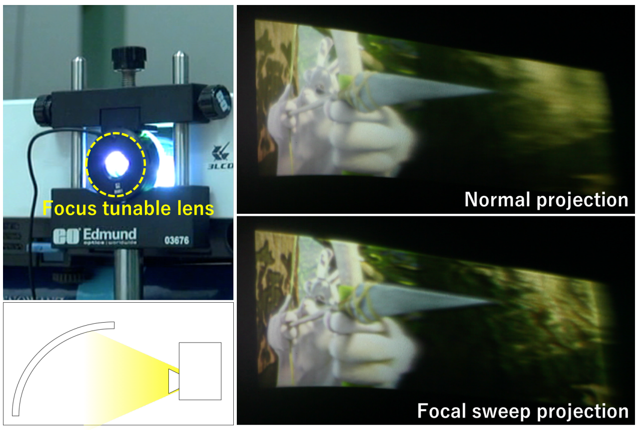

Figure 8: *Example of extended DOF projection based on the focal sweep technique [IMS15]. Upper left: A prototype system. Lower left: Projection environment. Right: Projected results of a typical projection (upper) and focal sweep projection (lower), respectively.*

As a pioneering work of the multi-projector approach, Bimber and Emmerling realize multifocal projection using multiple projectors each with a focal plane at a unique distance [BE06]. For each point on a projection surface, they selected an optimal projector that could display the sharpest image at that spatial point location. Their multi-projector approach does not require deconvolution. However, when an object moves, it does require the projection of spatial pattern images on the surface to estimate PSFs from every projector. In addition, the black level rises with each superimposed projection. Nagase et al. proposed a model-based method that can select the optimal projector for each surface point even when the surface moves [NIS11]. This is achieved by estimating PSFs from geometric information, such as the shape of the surface and the relative pose of the surface to projectors. Multi-projector system with focal sweep technique realized a wide field-of-view and extended DOF projection [NHT13]. A more general solution is to apply a multi-projector light transport matrix that models the influence of each projector pixel on a camera image that is regarded as an observed image [WB07, AYL*12, BBG*13]. Each projector image can be determined by computing the inverse light transport matrix.

4.5. Light Field Projection

Glasses-free 3D or light field projection systems, which provide physically correct views for a wide range of perspectives where

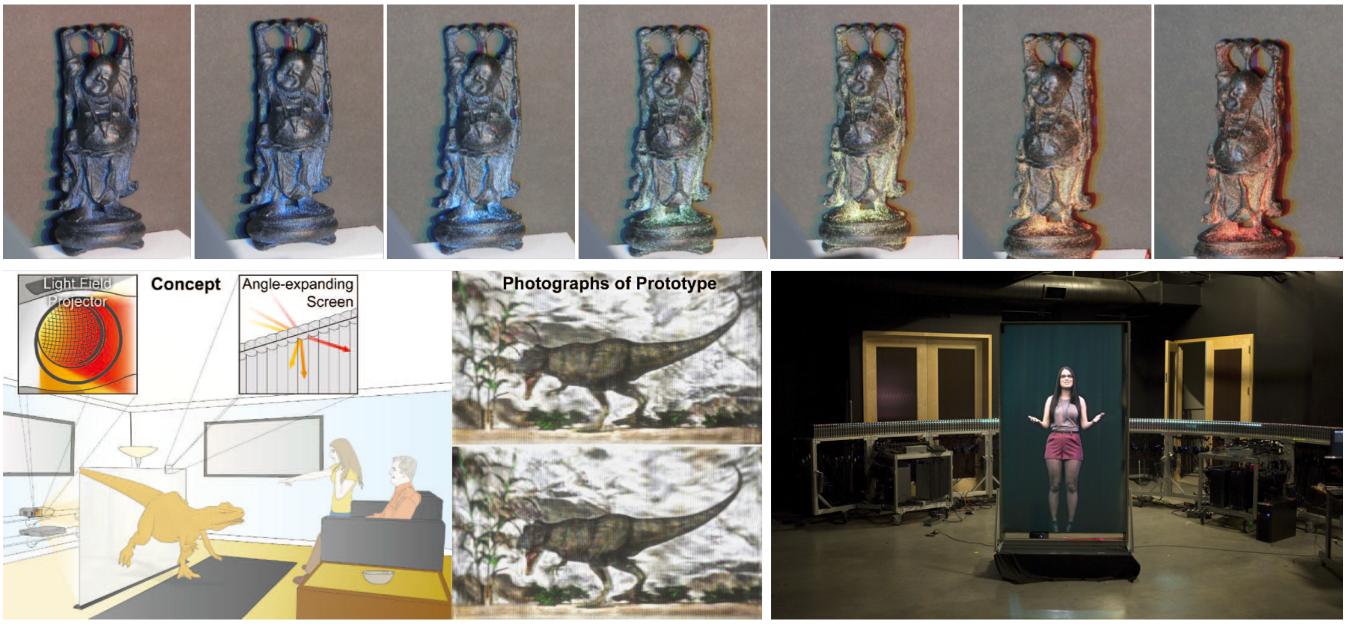

Figure 9: *Examples of light field projection. Upper: Light field projection mapping with multiple projectors projecting view dependent graphics from various directions onto an object on which a retro-reflective material is painted [AM15] ©Eurographics Association 2015. Lower left: Compressive light field projection system with a single projector consisting of two SLMs and a angle-expanding screen (right images are a displayed result captured from different directions) [HWR14]. Lower right: Light field display with a unidirectional diffuser onto which multiple projectors project view dependent graphics from various directions [JUN*15].*

observers do not need to wear special glasses, have been investigated throughout the last century. Although most of the systems apply integral imaging or parallax barriers, there is a fundamental and critical limitation in these principles—the loss of spatial resolution and light throughput. Several solutions have been proposed to overcome the resolution limits in the last decade (Figure 9).

Multiple projectors are combined with front or rear projection lenticular screens [MP04, Hsu08] or unidirectional diffusers [BKB07, Yos15, JUN*15]. In these systems, the number of projectors roughly matches the number of view directions. Instead of the flat screens, a non-planar surface on which retro-reflective material is painted is also used as a projection object [AM15]. When multiple projectors illuminate the object from different directions, view-dependent colors or anisotropic BRDF representation can be observed on it. Jurik et al. proposed a different principle where no projection screen is used but each projector of a projector array represents a pixel that emits view dependent colors [JJBD11].

In addition to the multi-projection approaches, single-projection solutions have also been proposed, which achieve light field projections with fewer components. For example, researchers proposed to use an array of LEDs that time-sequentially illuminate a digital micromirror device (DMD) from different directions for different viewing directions at a high-speed [BMR*10, MBR*10]. The projected images then illuminate a rear projection screen with micro-optical features, which is mechanically translated to control the propagation direction of the images. A compressive light field projection system was also proposed [HWR14]. The system consists of a high-speed, LCoS-based dual layer light field projector and a passive angle-expanding screen. Non-negative light field factorization is applied to decompose an original light field for the LCoS panels.

4.6. Multispectral projection

Current three color channel, i.e., RGB, projectors can only reproduce limited color spaces. Improving the color gamut has been an active research topic in projection display design over decades. Pioneering multi-primary designs increase the number of color primaries either using grating (7 primaries) [AOYO99] or color filters [AOYO00] (6 primaries) for a larger color gamut.

While the spectral power distributions of the primaries in the early systems are fixed, recent works apply adaptive color primaries for multispectral projections for better color reproduction and higher light throughput. Various adaptive color primaries have been investigated such as LEDs [KYS*15], a pair of prism and DMD [RBNB07], a pair of diffraction grating and attenuating mask [MRT08], and a programmable spectral light source [HIH16]. The main technical issues for these systems are primary design/selection and gamut mapping. For example, the spectral power distributions of primaries are designed to cover those of real world objects registered in a reflectance database, and then the gamut mapping is solved by a least squares algorithm [HIH16]. In another work, both primary selection and gamut mapping are jointly solved by non-negative matrix factorization that decom-

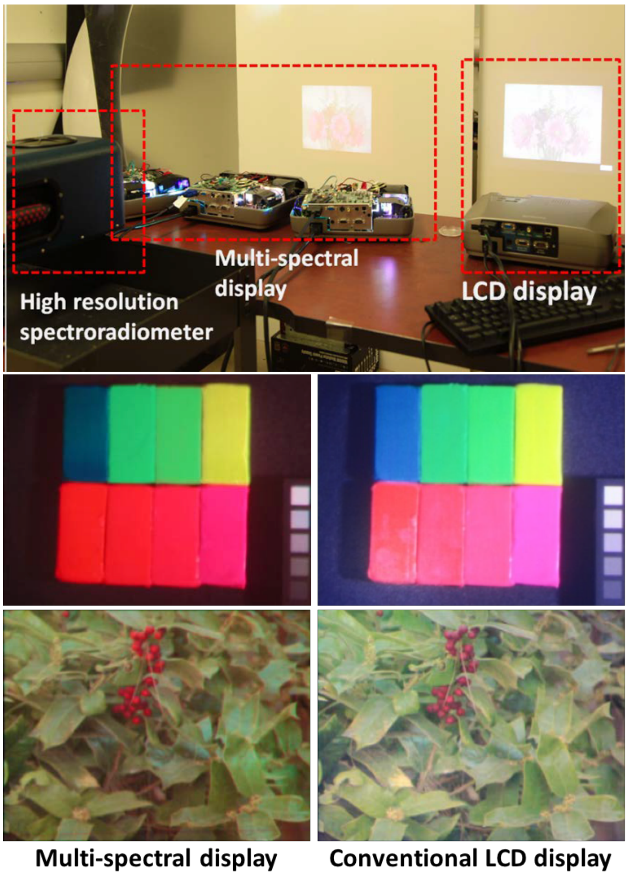

Figure 10: *Multispectral projection system using superimposed projectors with varying wide-band spectral color filters. [LMLG15]. In comparison with a standard LCD projector, the color saturation and color gamut is enhanced.*

poses a target image into a set of adaptive color primaries and corresponding pixel values [KYS*15].

The works described above basically apply narrow band primaries to improve the color gamut. However, while these reproduce an acceptable metameric spectrum as perceived by the CIE standard observer, it is generally a low fidelity approximation of the real spectrum which is not correct for other observers. Li et al. take an opposite strategy, i.e., explore the use of wide band primaries for accurate spectral reproduction [LMLG15] (cf. Figure 10). In addition to the lower spectral mismatch, the wide band primaries have higher light throughput than narrow ones making the system more efficient.

4.7. Summary

This section described computational projection display technologies to overcome technical limitations stemming from projector hardware and improve projected image quality for arbitrary, imperfect surfaces beyond the capability of algorithmic solutions. We summarize the state-of-the-art technologies introduced in this section, and point out the avenues of future directions of the field.

- HDR projection was achieved by either dual modulation or reallocation of light source (Section 4.1). In addition, upcoming laser projector technologies theoretically provide infinite dynamic range. On the other hand, environmental light is critical; i.e., the HDR is achieved only in a dark room. The current surface reflectance modulation techniques overcome the limitation as long as a static image is displayed.
- High speed and low latency projection systems have emerged very recently, which provide more natural augmentation in dynamic projection mapping and interactive systems than conventional projectors (Section 4.2). It is still an ongoing research issue to efficiently render and transfer projection images to minimize perceivable latencies.
- High resolution projection was achieved by subpixel shift of multiple image planes which are overlapped each other on a surface (Section 4.3). A remaining technical challenge is to avoid contrast reduction caused by overlapped multiple non-negative images. We should also solve the significant reduction of apparent spatial resolution when a user observes a projected surface very closely, which frequently happens in interactive systems.
- To increase the focal depth, previous techniques compute the inverse of the light transport matrix, which is a general representation of PSF (Section 4.4). A remaining technical problem is the contrast reduction due to the non-negative nature of projected light.
- Light field projection was realized by projecting view-dependent images from different directions onto a screen of a special optical property such as angle-expanding screen or retro-reflective surface (Section 4.5). It is still unsolvable to realize a light field display on normal, real-world surfaces.
- Multispectral projection was achieved by applying more than three color primaries (Section 4.6). Although these displays can more accurately reproduce the original colors, the displayed colors are still the approximation of the original spectral distributions. Full spectral color reproduction within a single projector setup is a future issue.

5. Applications

Tremendous advancements in the fundamental technologies, such as geometric calibration and radiometric compensation, have been expanding the application fields of projection mapping. We introduce recent trends of projection mapping applications based on procams in the last decade. We cover applications in which geometric registration and radiometric compensation are core components in Sections 5.1 and 5.2, respectively. We also introduce industrial and entertainment applications in Section 5.3.

5.1. Geometric Registration

A projection mapping application based on procams requires the geometric registration of the projector to a surface. The registrations are achieved either by normal 2D cameras or depth cameras that measure the surface pose or shape. We introduce application systems applying 2D cameras, followed by those applying depth cameras.

5.1.1. 2D Camera

Researchers proposed a projection-based game environment where a user can fabricate a game field, whose shape is measured by a procams for the geometric registration of the projector, and play with game widgets projected onto the surface [JSC*10]. Such registration technology is also installed in a theme park ride where multiple projectors are precisely registered to non-planar surfaces and players can change the surface textures with gun-like input devices [MvBG*12]. An interactive architectural daylight modeling is achieved with movable mockup walls, and projection-based lighting simulations [SYYC11, NC13]. When a user moves the walls, the system measures their poses by an overhead camera, and updates the projected lighting simulation. The same technology is also used in a projection-based game [DNC12].

Coaxial projector-camera setups are often applied in dynamic projection mapping applications. Most of these applications apply an IR camera to avoid interference between projected and captured images. Narita et al. applied a coaxial procams to augment deformable surfaces to support fabric design [NWI17]. They used an infrared ink that is visible by an IR camera, while being invisible to human eyes. A coaxial setup is also applied to augment human faces and achieve dynamic makeups [BBIG17]. It is also used to augment human hands to change their colors or textures to change the haptic perceptions such as softness [PIS15b] and heat [HIY*14], leveraging the crossmodal effects. Willis et al. assemble a handheld projector that can project IR and visible images from the same projection lens for displaying IR AR markers and visible images at the same time [WPHM11]. Multi-projection applications were achieved in which each projector projects unique ID by IR light sources while displaying visible images which interact each other.

5.1.2. Depth Camera

A variety of applications have been proposed for projector-depth camera systems (pro-dcams). One of the most active research domains of pro-dcams applications is projection mapping games. Several types of game platforms have been developed, such as extending the display area of TV games over surfaces around the TV screen [JBOW13], turning the whole room surface into a game space either with multiple projectors [JSM*14] or a steerable projector [WBIH12], and supporting face-to-face game with 3D virtual objects [BWZ14].

Pro-dcams have been used to augment real environments as interactive surfaces on which users can manipulate projected information such as images by touch actions. For example, researchers allow a user to directly interact with projected digital images on a wall and a tabletop using her/his hand [WB10]. Such interaction was also achieved for a handheld projector system as well [MIK*12]. Furthermore, the hand and arm of a user were turned into interactive surfaces [HBW11]. Such a concept was initially proposed by Yamamoto et al. [YS07], while they used an RGB camera. The depth camera supports richer touch interactions. Hand augmentation was also applied to visually guide a hand movement [SBW12].

Other researchers proposed to support sculpting by measuring the shape of a sculpted clay using the depth camera and visualizing the shape difference between the target and current shapes directly on the surface [RAD12].

5.2. Radiometric Compensation

Radiometric compensation (RC) allows the display of desired colors on arbitrary surfaces that have spatially-varying reflectance properties. Grundhöfer et al. proposed to turn everyday surfaces into blue screens by controlling the surface colors for chroma-keying in video composition [GB08]. Aliaga et al. applied an RC technique to virtually restoring the color of historically important objects in projection mapping [ALY08]. Menk et al. applied a model-based accurate RC technique to the assessment of the material appearance design of a car [MJK11, MK13, MK10]. The face expression of an animatronic avatar was manipulated by projection mapping where the texture of the face was altered by compensating the surface reflectance, inter-reflection, and subsurface scattering [BBG*13].

RC has been also applied in interactive applications. It was applied to make physical documents/books pseudo-transparent to support document search on a physical desktop [IS11]. The pseudo-transparent effect was achieved by changing the colors of a document placed on the top of a document stack from the original texture to those of lower layer documents. The same group also applied an RC technique to optically embed graphical information in shadows [IIS14]. Two images are projected from front and rear projectors onto a surface and overlaid onto each other. When a user's hand approaches the surface, a part of the front projection is occluded and the rear projection image appears. An RC technique is used to display different image contents for shadow and non-shadow areas. Amano et al. applied an RC to build a tool to support visually impaired people [AK10a]. The tool rotates the hue of a printed information by projection mapping so that visually impaired people can perceive them.

5.3. Industrial and Entertainment Applications

Procams are used for several industrial applications. When combined with accurate tracking, the projected optical superposition can be a helpful tool for construction, inspection work and reporting [SPHK08]. Several companies offer ready-to-use procams systems for such tasks [DIO, EXT]. The value of projection mapping as a collaborative design tool for architectural design was investigated [CL17]. Its impact on tourism marketing is also discussed [PP16].

Projection mapping became widely popular within the entertainment industry. Besides building projections, which have nowadays probably been seen by almost anyone in the world, attempts were made to integrate projections into theatrical stages, music concerts and sports stadiums [AN13].

6. Conclusion

This report covered the recent advances in the research fields related to projection mapping applications. We summarized the novel enhancements to simplify the 3D geometric calibration task which

Table 1: *Potential remaining issues for future research.*

	Topic (Section no.)	Issue
Algorithms	Geometric calibration (3.1)	Full online-self calibration
	Dynamic projection mapping (3.2)	Dynamic full body augmentations
	Radiometric control (3.3)	More accurate control for non-lambertian surfaces
Hardware	High dynamic range projection (4.1)	Dynamic HDR under environmental light
	High speed projection (4.2)	Efficient rendering and data transferring
	High resolution projection (4.3)	Dealing with close-up situations in interactive systems
	Increasing focal depth (4.4)	Avoiding contrast reduction
	Light field projection (4.5)	Light field manipulation on arbitrary surfaces
	Multispectral projection (4.6)	Full spectral color reproduction by a single projector

now can be reliably carried out either interactively or fully automated using adapted self-calibration methods. Furthermore, the improvements regarding radiometric and photometric calibration and compensation as well as the neutralization of global illumination effects were summarized. Innovations on the hardware side were also introduced in the latter part of the report. We covered recent technologies improving the dynamic range, frame rate, spatial resolution, and DOF. We also introduced the attempts for light field and multispectral projections.

Table 1 summarizes remaining technical problems which we believe determine the research issues in the next decade (also see Sections 3.4 and 4.7). The use of active materials such as photochromic inks as projection surfaces might be one of the first publications of a hopefully growing new research direction [ITHS14, TIS16]. It was shown how the screen structure can be modified to increase contrast and brightness in a desired, directional way [PWJ*17]. Related to that, Mine et al. [MIHS17] recently showed how light can be reallocated when projecting onto a non-planar rear-projection surface such that a uniform pixel density is preserved. This research shows that there seems to be a new upcoming research trend on computational projection surfaces.

In summary, we think that the future research of projection mapping will even more rely on the combination of a variety of different disciplines. In particular, since the projection hardware is limited within multidimensional aspects ranging from diffraction effects and bandwidth problems if the pixels count increases further, to energy efficiency in general, frame-rate, as well as lens quality and light throughput. Since overcoming these limitations will become more and more complicated, joint efforts in combining material and optics research, getting a better in-depth understanding of human visual perception, efficiently use real-time graphics and applying efficient mathematical methods might allow us to further improve the quality of projections systems.

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