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Projection Alignment Correction for In-Vehicle Projector-Camera System

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Abstract

In this study, we propose a projection registration method for the projections from a continuously moving vehicle for driver vision assistance during night driving. Accordingly, we employ a context-aware projection technique with adaptive pixel mapping generation. Because vehicle movements lead to misalignment of the projection latency, a co-axial projector-camera configuration or high frame rate processing cannot solve this problem. However, adaptive pixel mapping corrects pixel mapping according to the vehicle speed and achieves a misalignment-free dynamic projection mapping. The effectiveness of the proposed method was evaluated through experiments using a moving projector-camera system mounted on a motorized linear stage.

CCS Concepts
• ***Human-centered computing*** → ***Mixed / augmented reality;*** • ***Computing methodologies*** → ***Mixed / augmented reality;***

1. Introduction

Night vision system for advanced driver assistance has been under development for over two decades [Sch99], and its function is now available for commercial car options. A head-up display (HUD) shows the navigation information on the windshield and it prevents drivers from being distracted from the road. However, drivers must understand the correspondence between the displayed information on a specific HUD area and the actual road scene. Hosseini et al. [HBL14] proposed an automotive augmented reality system for driver assistance that showed graphical information at the exact position according to the viewing position of drivers. The system requires a full-windshield display with 3D position estimation using a stereo vision for the geometrically correct display.

In recent years, pixelated headlights have been developed [Ulr15]. The device blocks high beams for oncoming vehicles and pedestrians. In addition to anti-glare high beams, Tambro et al. proposed improvements in visibility lighting during snowstorms [TNC*14]. In other applications, it projects turn arrows or other helpful graphics, such as a crosswalk. The development of the micro-LED technology provided an LED array, and it is expected to replace the DLP chip or other Micro Electro Mechanical Systems in the near future [Woo19].

The spatial augmented reality technology displays augmented information on the object surface using projectors or other optical display devices. Amano et al. [AK10a] proposed appearance manipulation with illumination projection. It enables the alternation of apparent color or visual features in real time. This technique is also applied for visual assistancet [AK10b]. By combining appearance manipulation with a pixelated headlight, head position-independent visual annotations can be projected without the complex mechanism shown in Fig.1. However, the system has a latency and it creates a projection misalignment. In this study, we propose a novel misalignment-free dynamic projection mapping technique for a continuous moving projection target with projector-camera closed-loop processing.

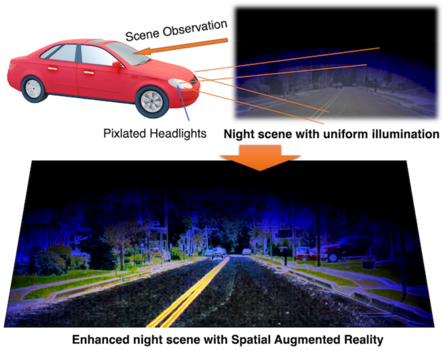

Figure 1: *The enhancing illumination pattern is projected on the roadway from the pixelated headlights for advanced driver assistance.*

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2. Related work

2.1. Dynamic Projection Mapping

To solve projection registration problems for automobile illumination with pixelated headlights, dynamic projection mapping can be a key technique. Bandyopadhyay et al. [BRF01] proposed a pioneering study on dynamic projection mapping. Their work enabled the projection of the texture drawn by user interaction on a freely movable rigid object with an optical tracker. Since then, significant research work has been conducted over the last 20 years. However, the projection target road scene has no common visual fiducial point for projection registration owing to various road scenes. Resch et al. [RKK16] proposed a dynamic projection mapping technique for tracking complex-shaped physical objects. Such markerless approach estimates real object movements with six degrees of freedom to register a projection pattern. For this solution, we can use another type of vision sensor, such as a Kinect depth sensor [SCT*15] or infrared camera [HKK17].

The posture as well as its shape changes depending on various road scenes. As a solution, a dynamic projection mapping technique for deformable objects can be applied. Visible dot clusters [NWI17] or invisible markers based on infrared ink [PIS14] painted onto the surface are used for deformation measurement. However, these approaches are not applicable since no existing common visual fiducial point on road scenes. Markerless approaches for projection mapping on a deformable object, such as a human face [BBIG17] and human arm [PW21], have also been proposed. However, these approaches focus on elastic deformation and they are too expensive for the projection registration problem of automobile illumination.

2.2. Context-aware Projection

The most challenging problem with automobile illumination is the registration of context-aware information projections in closed-loop processing. In other words, the projection content must be dynamically generated from the road scene.

Fujii et al. [FGN05] proposed a real-time radiometric compensation method for dynamic environments. They aligned a projector and camera coaxially with a plate beam splitter and generated projection illumination based on the estimated reflectance for radiometric compensation on the textured surface. In contrast to compensation, Wang et al. [WFF*10] proposed a context-aware light source that enhances object features, such as contours with illumination projection. Amano et al. [AK10b] proposed a visual edge enhancement technique for the visually impaired based on projector-camera feedback. The appearance manipulation is also applied for markerless real-time materiality representation alternation such that an image processing-based materiality manipulation algorithm [Ama13], surface normal acquisition uses three near-IR cameras with three channels near-IR light sources [MWI18].

3. Projection Registration for Moving Projector-Camera System

The use of co-axial projector-camera optics resolves the projection registration problem on the varied shapes of surfaces. This means that notifications can be dynamically projected on the road scene without a 3D shape model. However, such feedback processing always has latency, which eliminates the benefit of pixel mapping invariance against projection depth change. A high frame rate and low latency feedback process reduce the misalignment. A special projector avoiding video interface [ZWL*14] improves this problem but still remains the latency for other image processing includes capturing. Only alignment correction with movement prediction solves this problem even with inexpensive non-co-axial equipment with low frame rate.

The optical flow provides a good prediction of object displacement in the next frame without any prior information of the scene. However, per-pixel dense flow estimation is difficult for sparse visual features on the road. The epipolar geometry provides a line constraint for the flow direction in the captured image under the assumption of a pinhole camera model. However, a general wide-viewing angle camera has distortion and it easily breaks the pixel correspondence. Therefore, we propose pixel mapping-based misalignment correction.

3.1. Adaptive Pixel Mapping Generation

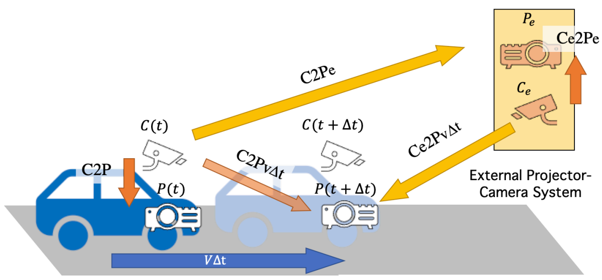


Figure 2: *Relation between a captured image $C(t)$ and a projection image $P(t)$ for a moving in-vehicle projector-camera system.*

Fig.2 illustrates the relation between captured images and projection images for the vehicle movement. In this figure, $C(t)$ and $P(t)$ denote the captured image and projection image at time t, respectively. Ce and Pe denote the captured and projected images using the external projector-camera system used for calibration, respectively. When the vehicle stays in place, the corresponding pixel does not change over time, and pixel mapping, $C2P$, calibrated with $C(t)$ and $P(t)$ can be used in this situation. In contrast, when the vehicle is moving with speed V, the annotation is projected at the forward position with a displacement of $V\Delta t$ for its processing latency of Δt. Therefore, once we obtain pixel mapping $C2P_{V\Delta t}$ from $C(t)$ and $P(t+\Delta t)$, the system can correct the misalignment due to latency for the moving speed of V. However, the projector and camera must be fixed to a rigid vehicle body for precise pixel mapping. Thus, we cannot directly acquire $C2P_{V\Delta t}$. To solve this problem, we propose the following calibration procedure with an external projector-camera system.

1. Calibrate $C2P$ from $P(t)$ and $C(t)$ at the initial vehicle position.
2. Calibrate $C2Pe$ using the projection from the external projector.
3. Move the vehicle forward $V\Delta t$.
4. Calibrate $Ce2P_{V\Delta t}$ by $P(t+\Delta t)$ and Ce using an external camera.

With these pixel mappings on the external projector-camera system, $Ce2Pe$, that between $P(t+\Delta t)$ and $C(t)$ is calculated by

$$C2P_{V\Delta t} = Ce2P_{V\Delta t} \circ Ce2Pe^{-1} \circ C2Pe, \tag{1}$$

where $\circ$ and $C2P^{-1}$ denote composite mapping and inverse mapping, respectively. Using this pixel mapping, we can generate a pixel mapping for the given speed V' by linear interpolation adaptively as follows:

$$C2P_{V'\Delta t} = \frac{V'}{V}(C2P_{V\Delta t} - C2P) + C2P. \tag{2}$$

3.2. Processing Pipeline

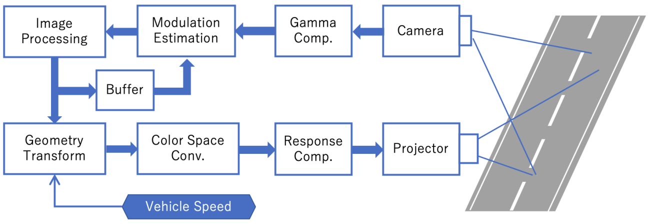


Figure 3: *Feedforward projection flow of our system. We achieved context-aware projection in feedforward processing with modulation estimation. The adaptive pixel mapping for a given vehicle speed corrects the misalignment produced by the processing latency in the geometry transformation.*

Our processing pipeline for context-aware projection is shown in Fig. 3. A conventional color camera captures road scenes with a response compensation, such as gamma correction. Subsequently, the system estimates a uniform lighting scene view that removes a projected pattern with the estimated modulation using a buffered previous projection pattern. Next, our system generates a projection image using the desired scene enhancement or annotation graphic drawing. Then, geometrical transformation with adaptive pixel mapping for a given vehicle speed is applied. Finally, the projection image is projected from the projector after color and response compensation.

The appearance control technique [AK10a] cumulates the manipulation error with the employed model-predictive controller. It provides robust appearance manipulation against environmental illumination changes or model errors. However, it takes a few frames to converge the projection. Hence, the system creates afterimages on the moving projection target during its convergence process, as shown in Fig. 5(a). Therefore, we employed feedforward processing shown in Fig.3 that removed negative feedback processing for radiometric error accumulation.

4. Projection Results

4.1. Hardware Setup

Fig.4 shows our experimental setup. For the vehicle projector-camera system, we used Ximea MQ013CG-E2 with a resolution of 1280 × 800 pixels as a camera and BenQ MH550 with 1600 × 900 pixels as a projector. This projector-camera system is mounted on a motorized linear stage and the stage moves the system back and forth at ± 250 mm at the desired speed. A roadway model was placed in front of the motorized linear stage and the external projector-camera system was placed above the model. The external projector-camera system consists of a camera and projector with resolutions of 1304 × 800 pixels and 1280 × 800 pixels, respectively. The blue area shows the projection area of the external projector. The vehicle projector-camera system and external projector-camera system were aligned to capture the roadway.

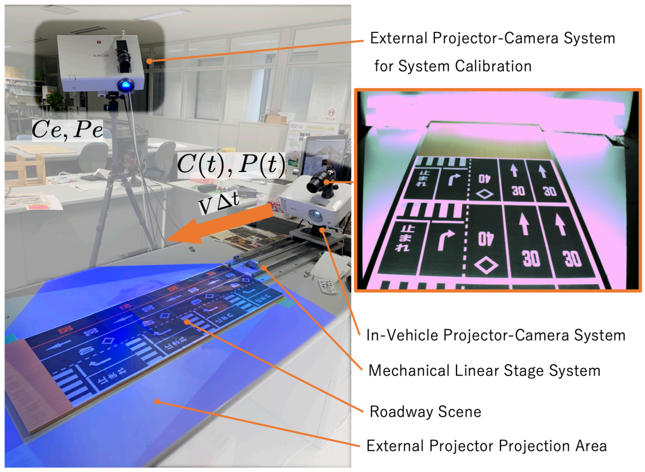
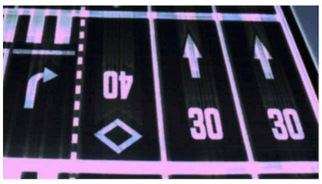
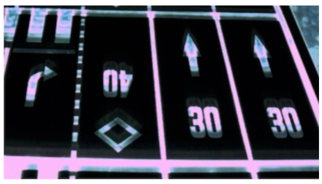
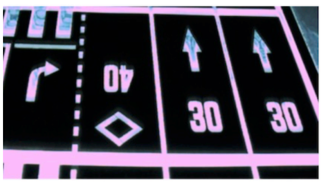


Figure 4: *The in-vehicle projector-camera system is mounted on a motorized linear stage and runs back and forth at the desired speed. A roadway model is placed in front of its system. An external projector-camera system was used for calibrating $C2P_{V\Delta t}$.*

4.2. Comparative Evaluation


(a) Appearance Control


(b) Feedforward Projection


(c) Proposed Method

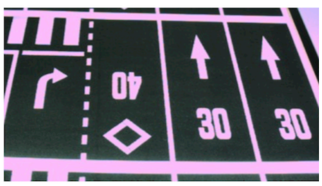
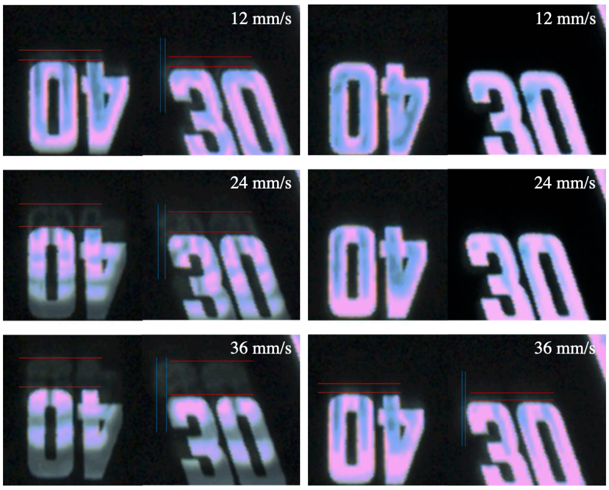

(d) White Illumination

Figure 5: *The appearance control produced an afterimage for its integrator element in the model-predictive controller. In contrast, the proposed method achieved perfectly overlapping projection by employing feedforward processing with adaptive pixel mapping.*

To validate the effectiveness of projection misalignment correction with our method, we compared appearance control [AK10b], feedforward projection without misalignment correction, and the proposed method. Fig.5 shows the projection result when the on-vehicle projector-camera system is running at 20 mm/s in the motorized stage. For this evaluation, we applied edge enhancement as an image processing for both appearance control [AK10b] and the proposed method, as shown in Fig. 3.

As mentioned earlier, the cumulation in the feedback creates afterimages, as shown in (a). Note that the afterimage is projected toward the running direction because the vehicle is running forward and the road scene is going downard. When we employ simple feedforward processing (b) in exchange for robustness, the afterimage disappears, but misalignment still exists. In contrast to these results, the proposed method (c) demonstrated a perfectly overlapping projection result while the in-vehicle projector-camera system was running. Evidently, simple plane illumination (d) never creates afterimages, however, it cannot improve visibility.

4.3. Misalignment on Each Speed



(a) Fixed Pixel Mapping (b) Adaptive Pixel Mapping

Figure 6: *Misalignments were removed with adaptive pixel mapping generation, except for the case of 36 mm/s.*

Because the running speed of an actual vehicle changes according to driving, we evaluated the misalignment for each running speed with pixel mapping generation using Equation 2. Fig.6 shows projection misalignment observed for each projection method. Fixed pixel mapping (a) shows results with feedforward projection without misalignment correction, and adaptive pixel mapping (b) shows results with the proposed method. Evidently, the misalignment toward the moving direction increases with the running speed with fixed pixel mapping. In contrast, adaptive pixel mapping reduces misalignments at 12 and 24 mm/s. However, the misalignment remained in the case of 36 mm/s owing to the linear prediction for adaptive pixel mapping generation. It should be noted that since we applied the edge enhancement for visibility improvement, the outline of the letter has been enhanced. If it harms visibility, we can apply other enhancements to the image processing. Figure.7 shows the average of misalignment for the nine grid points sampled from the entire road surface observed by the in-vehicle camera.

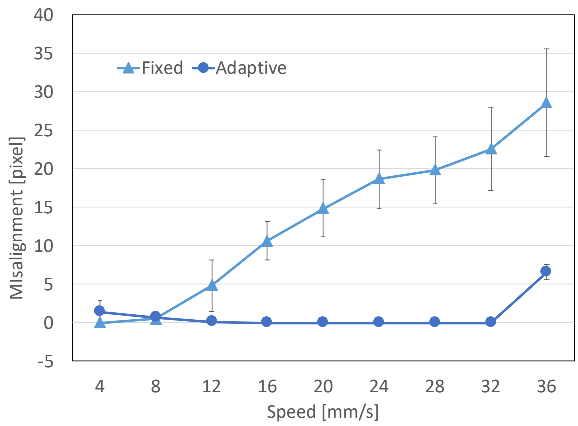


Figure 7: *Averaged misalignment for each in-vehicle projector-camera system moving speed. Adaptive pixel mapping corrected the misalignment for speeds ranging from 12 to 32 mm/s.*

Because we calibrated the pixel mapping $C2P_{V\Delta t}$ for the 20 mm/s (displacement $V\Delta t = 20mm$), misalignments were completely removed at the middle speed ranging from 12 to 32 mm/s. However, misalignments are produced outside the range of nonlinearity of misalignment in the captured image.

5. Discussion

We employed linear prediction for adaptive pixel mapping generation. However, it produces a misalignment in a range of speed that are faster and slower than the calibrated speed. As a solution to this problem, we can employ a piecewise linear function. However, it increases the calibration cost because it requires the measurement of $C2P_{V\Delta t}$ for a few displacements. As another solution, we can use the cascading application of $C2P_{V\Delta t}$. We will address this problem in our future work.

6. Conclusion

In this study, we proposed a novel projection registration method for illumination projection from a continuously moving vehicle for driver vision assistance during night driving. The proposed adaptive pixel mapping technique for projector-camera systems corrects the misalignment produced by vehicle movements within a projection latency. Such misalignment cannot be compensated by a co-axial projector-camera configuration or fast frame rate processing. The experimental results demonstrated the accuracy of the proposed misalignment correction method. However, misalignments were observed at speeds beyond the range of the calibrated running speed. In addition, we will also address practical problems, such as applications on a curved road and headlight regulations of illumination color and uniformity, in future works.

Acknowledgement

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