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Real-time Content Projection onto a Tunnel from a Moving Subway Train

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Abstract

In this study, we present the first actual working system that can project content onto a tunnel wall from a moving subway train so that passengers can enjoy the display of digital content through a train window. To effectively estimate the position of the train in a tunnel, we propose counting sleepers, which are installed at regular interval along the railway, using a distance sensor. The tunnel profile is constructed using pointclouds captured by a depth camera installed next to the projector. The tunnel profile is used to identify projectable sections that will not contain too much interference by possible occluders. The tunnel profile is also used to retrieve the depth at a specific location so that a properly warped content can be projected for viewing by passengers through the window when the train is moving at runtime. Here, we show that the proposed system can operate on an actual train.

CCS Concepts
• ***Computing methodologies*** → *Mixed / augmented reality;*

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1. Introduction

Today, subways have become an essential part of urban society as a means of transportation. Windows on a subway train in general serve to admit light from outside, show distant scenery, and deliver information when passengers look for a specific destination. However, windows on the subway train do not serve any of these purposes except at platforms because the train mostly operates inside a tunnel. Therefore, although the windows on a subway train are located in the best position in terms of the passengers' viewpoint, their existence is meaningless most of the time while the train moves. One remedy would be to use them to show digital content and make the passengers feel like that the train is passing through an interesting space instead of a dark tunnel.

There have been attempts to display digital content though a subway train window. One representative approach is to install displays directly on the wall of a subway tunnel [Spa92, JHLB15]. While this approach successfully transforms a dark tunnel into a canvas for eye-catching digital content, it suffers from the following disadvantages. First, the installation and maintenance of the system must be performed inside the tunnel. These tasks are restricted to only when the trains are not in operation, typically in the middle of the night, to comply with safety regulations. Second, the built-in tunnel display system requires the installation of as many display panels that correspond to the duration of the content. This means that the installation and maintenance could be costly for lengthy content. Third, to properly display content precisely when the train passes by so that the passengers can feel that they are watching a moving picture through the window, the train must run at a certain speed or faster. Therefore, the system cannot be installed in sections where the train runs slower, such as near platforms or in curved sections. Finally, synchronization between the train speed and the display position must be carefully maintained. Otherwise, the passengers may observe a content sliding artifact. Unfortunately, this artifact occurs frequently due to slight changes of a train's speed.

We propose a novel approach that allows projection of digital content on the tunnel wall from a projector installed on a subway train. Because the projector and the related system are mounted on the train and move with it, the aforementioned disadvantages associated with a built-in tunnel display system can be easily resolved. For example, system setup is greatly simplified and, consequently, the installation and maintenance can be performed in the base station much more safely. The decoupling of content duration from the system setup allows more freedom to the digital content creators than previously allowed. In addition, the content can be displayed in more sections of a tunnel in general because the display is not subject to any speed constraints.

2. Related Work

To show visual content through the window of a moving subway train, a previous attempt was made to install a display system on the

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tunnel wall [Spa92]. This method installed a series of display panels and showed seamless content by exposing the screen at a designated time to a passing-by train. This method was further improved to show content using LED arrays by taking advantage of the fast movement of the train [JHLB15]. Instead of attaching the displays to a tunnel wall, a conceptual idea of installing a projector to a moving train was proposed as a patent [KS96, Vay08]. Although these patents explained the concept of projection onto a tunnel wall, detailed methodology for practical implementation was not disclosed. Recently, another interesting attempt was made in which the train window is replaced with a transparent display to show digital content [Shi21]. This high-quality display system requires changes to the interior design of the train, and the price tag is very high for a train window-sized transparent display panel. We propose the first real-world working projection system of visual content onto a subway tunnel wall, which is relatively inexpensive and can be easily adopted to existing subway trains.

Real-time projection onto a tunnel wall from a moving train is related to a dynamic projection mapping problem. Dynamic projection requires finding a rigid transformation between the projector and the surface. The positional information of the surface can be captured by using retroflective markers [MSWT14], fiducial markers [RVBB*06] or magnetic trackers [BRF01]. We discard these marker-based approaches to avoid direct installation inside the tunnel for easy and safe maintenance. Markerless approaches utilize shape features observed from the projection surface. These methods estimate the pose of the surface by matching its original model with measured information using grayscale [RKK14], infrared [HKK17], or depth images [ZXT*16]. Because a subway tunnel has few features to use, we estimate the surface of the tunnel through a calibrated depth camera and project content to it so that it can fit the window when viewed from inside the train. Bimber et al. [BIWG08] surveyed effective solutions for general problems encountered in various projection environments. Unfortunately, none of the existing approaches are applicable to real-time dynamic projection from the bottom of a moving train in an extremely challenging environment that restricts the size of the hardware and its installation location. To achieve our goal, we newly propose the use of appropriate sensors and present novel methods for sleeper counting and depth profile generation in the presence of occluders.

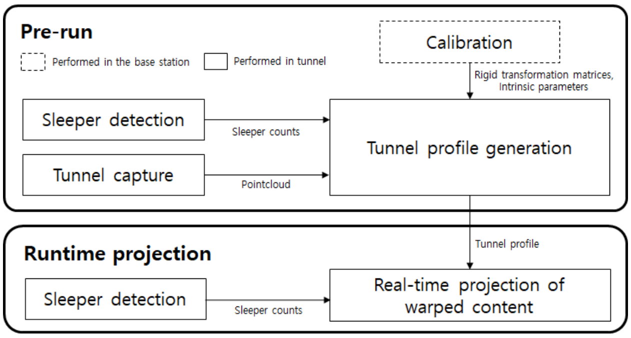

Figure 1: *System overview. The calibration between the devices is performed first in the base station followed by the generation of a tunnel depth profile by the moving train in the pre-run step. Properly warped content, according to the depth profile, is projected onto the tunnel wall at runtime.*

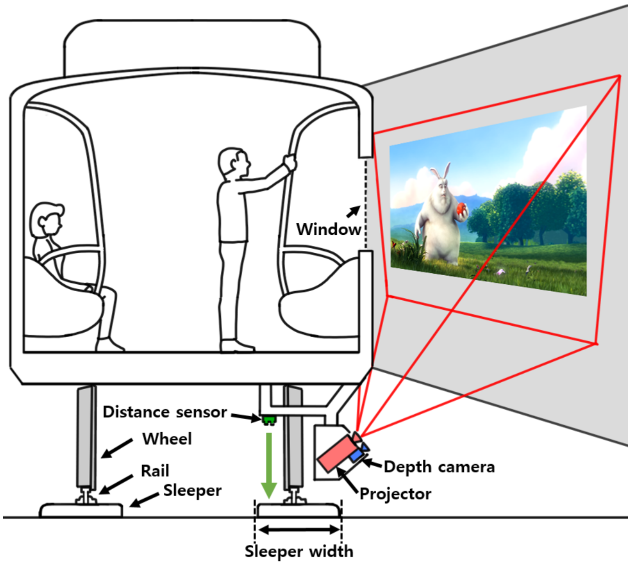

Figure 2: *System installation. The red line indicates a frustum created by the projector beam. The green arrow indicates the direction of the distance sensor for detecting sleepers.*

3. Overview

Our goal is to achieve the real-time projection of warped content on the tunnel wall so that passengers in the subway train can enjoy the content properly through the window. Our method consists of two steps, as shown in Figure 1. In the pre-run step, the calibration between the devices is performed at the base station. Specifically, rigid transformations among the depth camera, the projector, and the train window are computed, and intrinsic parameters associated with the projector are also estimated. A calibrated depth camera is used by the moving train to capture a pointcloud that represents the tunnel wall. Sleeper counting is performed simultaneously to track the location of the moving train. Using the pointcloud and the corresponding locations estimated from the sleeper counting, a tunnel depth profile is constructed and then projectable sections are identified. At runtime, the train location is computed again by the sleeper counting in real time. Then, warped content is projected onto the tunnel wall at the current location according to the depth from the tunnel profile for suitable viewing by passengers through the window.

4. System Setup

Our projection system consists of a single projector and a depth camera. Both devices are installed facing the tunnel wall from the side of a train. The installation position of the devices is somewhat restricted. Installing the devices inside the train may cause inconvenience to passengers or interfere with them and cause shadows. There is a safety limit line to avoid collisions and high voltages outside the train, so the devices cannot be installed on the top or side. In general, a train provides brackets under its main body to accommodate equipment for various purposes. Therefore, our system is installed on the bottom of a train, as shown in Figure 2. A distance sensor for sleeper counting is also installed under the train, directly facing the sleeper from above.

For pre-processing, we first estimate the rigid transformations among the train window, the projector, and the depth camera to represent 3D points captured by the depth camera in different coordinates. The intrinsic parameters of the projector are also estimated for the proper display of content onto the tunnel wall. It is impossible to find the rigid transformations between the train window and the devices directly because the train window is not visible from the devices that are facing a tunnel wall. Therefore, to help calibrate our system indirectly, we employ a temporary depth camera and position it at the reference viewpoint looking out through the window.

The transformation between the train window and the temporary depth camera can be obtained by matching the actual four corners of the window and those on the image captured by the temporary depth camera [Mor78]. We estimate the intrinsic parameters of the projector and the transformation between the projector and the temporary depth camera simultaneously based on Jones et al. [JSM*14]. To find the transformation between the depth camera installed on the bottom of the train and the temporary depth camera, the intrinsic parameters of the depth camera installed at the bottom of the train are estimated first [Zha00]. The transformation is then estimated using the correspondences along with the intrinsic parameters of the depth camera installed at the bottom of the train [Mor78]. Finally, the transformations between the train window and each device are calculated by multiplying the transformation between the train window and the temporary depth camera and the transformation between the temporary depth camera and each device.

5. Tunnel Profile Generation

We generate a location-based tunnel depth profile using pointclouds captured by the depth camera installed at the bottom of the train. The profile is used to find projectable sections along the tunnel and is also used, together with the information regarding the projectable sections, for proper content projection onto the tunnel wall at runtime. The pointcloud is captured simultaneously when each sleeper count is updated as the train moves through the tunnel. To count the sleepers, the distance sensor installed under the train in used. Using a threshold value, the sensor toggles depending on whether it is above a sleeper or not. The pointcloud is then transformed to the window coordinate using the transformation between the window and the depth camera. Next, the pointcloud is cropped using the frustum created by the reference viewpoint through the window, which represents the visible area from the passenger. To find tunnel depth using the cropped point cloud, we first estimate a virtual plane that fits them by using the RANSAC algorithm [FRGPC*17].

Existing tunnels have been designed without consideration for projection and there can be occluders that cast shadows by blocking the light from the projector. To find an area occupied by each of the non-uniformly distributed points viewed from reference viewpoint, we project both of the inlier and outlier points onto the virtual plane, assuming that the outlier points are from an occluder. To estimate the area formed by the points, we compute a Voronoi diagram [Aur91] inside the window. Given that each point occupies the area defined by the cell in the diagram, we compute the proportion of the occlusion-free area to the entire potentially projectable area at the sleeper count by counting the pixels in each area. We define a projectable section about projectable surfaces of tunnel are continuous. The proportion threshold is set to 80% by default according to our observation of the projection area.

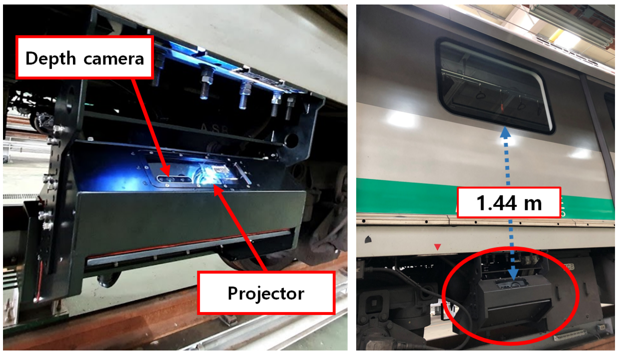

Figure 3: *The devices, their housing, and the installed positions at the bottom of the train for the experiment*

6. Runtime projection

When the train moves at runtime, the projector is in the ready state until the sleeper count reaches a projectable section. Once the train enters a projectable section, warped content is projected on the tunnel wall to be viewed through the window from the reference viewpoint. The surface of the tunnel at the current sleeper count is assumed to be planar. The four corners of the train window are determined, as explained in Section 4, and are transformed to the projector coordinate using the transformation computed in Section 4. Then, the transformed corner points are mapped onto the image in the projector coordinate using the intrinsic parameters. Each image frame of the content is warped to fit the target projection area using a 3×3 homography matrix $\mathbf{H}$ [GDC11].

7. Experiments

7.1. System setup

We installed the proposed system to an actual subway train in Daejeon Korea, as a testbed. To mount the system at the bottom of the train, we made a projector housing, a distance sensor housing for sleeper detection, and a controller housing as shown in Figure 3. The projector housing and the controller housing are made of stainless steel. We employed an Intel Realsense D435i with a resolution of 424 x 240 as an RGB-D camera and a SEEMILE PL-BF650ST with a resolution of 1920 x 1080 fullHD as a wide-angle projector, both of which were assembled in the projector housing. A camera with a global shutter is a suitable choice for use with a fast moving subway train. The projector was positioned at 1.44 m below the origin of the train window coordinate as shown in Figure 3.

Figure 4: *Results of visual content projection from a moving train viewed from various viewpoints*

7.2. Results

Figure 4 shows projection results produced at runtime viewed from differing viewpoints. The projection results confirm that our system can transform a dark tunnel into an effective display that can be enjoyed through a train window at different positions and angles with somewhat similar viewing experiences. Considering that the proper projection of the warped content is achieved automatically in real-time, we assert that our system has advantages over previous approaches [Spa92, JHLB15] that heavily rely on careful synchronization between the train and the display panel attached on the tunnel wall.

8. Conclusion

In this paper, we presented a real-time content projection system onto a tunnel wall using a projector installed at the bottom of a moving subway train. At runtime, our system projects the content onto the tunnel wall warped by the homography matrix constructed using the depth from the tunnel profile in a projectable section according to the undated sleeper count when the train is moving. Through experiments, we showed that our system works with real-world subway systems.

Our system has some limitations. Under the subway train, there may be dust, such as oil powder, for wheel stopping, which can interfere with the distance sensor and affect the brightness of the projector. Therefore, periodic cleaning of the projector housing and the distance sensor are required, which can be performed as part of the existing maintenance process of a train. The interior lights produce a reflection on the window making the content relatively dark. Applying an anti-reflective film on the window or using a brighter projector can be a remedy for this. Most subway tunnels are made of concrete with a simple texture, which is widely utilized material as an outdoor projection surface for media facade. Therefore, we focused on geometry manipulation for projection in this study. Compensating color to improve the quality of the projection can be an interesting future research direction.

9. Acknowledgements

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