Towards Mobile Projective AR for Construction Co-Robots

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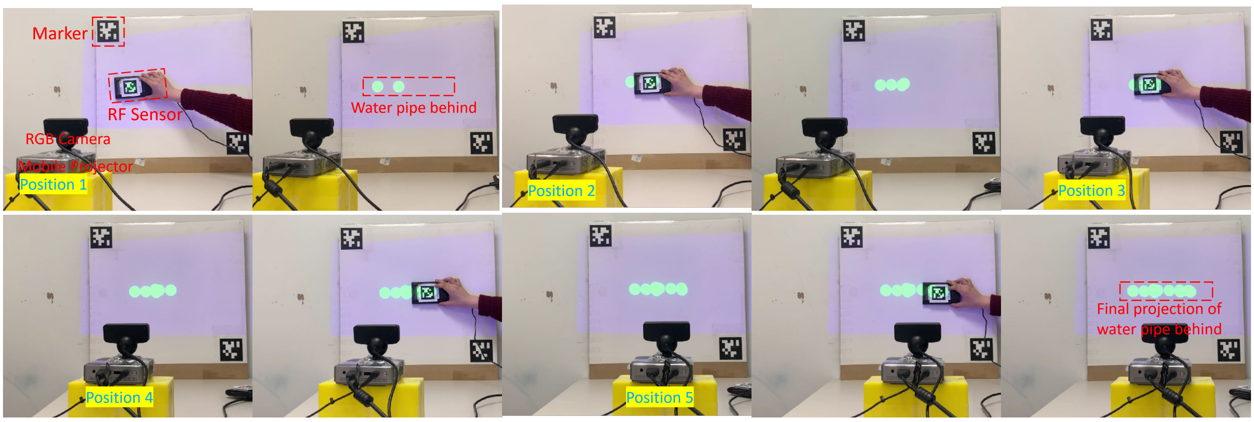

Figure 1. An assistive application of MPAR. An occluded utility is detected and visualized on the fly by projecting the detection results back onto the wall via a moving RF sensor. MPAR enables consistent visualization even after the projector changed its pose. The whole process can be seen in the video at: https://youtu.be/xvNBy$_{C}$0h3s.

Abstract -

The construction industry has been suffering from both low labor productivity growth and safety issues, due to the increasing project site complexities and the lack of skilled labors. As a potential technical solution, Augmented Reality (AR) has been studied to reduce the cognitive workloads in construction job sites by visualizing task-related information in the direct context of the workspace and operations. Instead of using helmets/goggles that may decrease users' field of views, we advocate mobile projectors for AR (MPAR), and propose a camera-projector system to ensure consistent AR projection even if the projectors may change poses when installed on mobile platforms such as human workers or even construction collaborative robots (co-robot). By obtaining the projector's pose relative to the projection plane (e.g., a wall or panel on construction site) via composing a series of homography transformations in this system, we could determine how to warp virtual information (images or 3D models) for desired projections, no matter whether human observers' head poses are needed. We demonstrate the effectiveness of the method using two construction AR applications: displaying occluded as-planned or as-built facility information behind a mock-up wall.

Keywords -

Projector-based AR; Camera-Projector System; Pose Estimation; Mobile Co-Robots

1 Introduction

The construction industry has been labeled as hazardous [1, 2] and susceptible to casualties and economic losses [3, 4]. Occupational Safety and Health Administration(OSHA) provides statistical data to state that the fatal injury rate in the construction industry is higher than the national average in any other industries in the US [5]. Many research works have been done to improve construction safety. Also, according to McKinsey [6], the construction industry has an intractable productivity problem and there is a large room to improve project efficiency and boost value. Therefore, higher construction productivity has become another pursuit of the construction industry. By blending task-related information directly in real context, AR technology offers the potential to increase construction safety and efficiency with easier access to retrieve on-site information [7]. One trend is integrating AR technology with Building Information Modeling (BIM) [7–11]. Their research works focused on employing AR as a visualization tool to display as-planned BIM information in the context of the real environment in architectural visualization, facility management, construction education, and other construction-related fields. Another trend is to design a mobile augmented reality (MAR) system for architectural, engineering, construction and facility management (AEC/FM), BIM information retrieval and construction education [12–15].

However, conventional AR has several limitations that could be potentially problematic for construction/civil applications. Unlike AR for gaming or education, which is operated in a relatively simple and safe environment, restricted field of view of conventional helmet-based AR will reduce the amount of environmental information available to people [16,17] and may cause fatal injuries to construction workers. Kawano et al. [18] reported that in their survey of using HoloLens (a pair of head-mounted smart glasses developed and manufactured by Microsoft) to train the construction team during the assembly process, in order to get a full view of the assembly site, workers have to move head instead of moving eyes naturally. Wearing AR devices may also cause distraction and reduce situational awareness, raising concerns about safety [19]. For tablet-based AR, the technology is relatively mature, however, it produces less immersive user experience [20] which could also impede the application of AR technology in the construction field. Also, for many tasks other than monitoring/inspection, workers cannot hold a tablet while working on the tasks.

The objective of this research is to develop a mobile projector-based AR technology to increase the safety and efficiency of the construction industry by enriching the information on the real construction site while avoiding the drawbacks of conventional AR. Our contributions are listed as follows:

- We introduce related projective geometry theory as fundamentals for our method.
- We design MPAR, a camera-projector system that can augment task information directly onto a physical workspace.
- Our MPAR system can be either independent or dependent on the observer's pose.
- We test MPAR in an assistive application that projects positions of occluded utilities behind a wall using an RF-image sensor.

2 Related Work

There have been some researches on introducing AR technology to construction. However, projector-based AR technology that can somehow overcome the drawbacks of conventional AR, has not received much attention. To realize AR technology using a projector, we need to dive into mobile AR technology and other related work, such as projective AR system's math model and pose estimation.

AR in construction. Kamat et al. [21] discussed an HMD/glass-based AR method for assessing the building damage caused by earthquake. Their method superimposes the previously stored building information onto the real structure and computes the difference between the two views. Bae et al. [12] proposed a tablet-based AR system for smartphone users to query 3D virtual information on-site. Their system reconstructs the camera pose by matching feature points of a photo and pre-stored point cloud, thereby obtaining the user's position. Mevza et al. [22] focused on implementing a BIM-based AR system to improve the performance of digital materialization. Their method feeds the mobile AR system with pre-generated AR model converted from BIM.

Projector-based AR. Given the above-mentioned limitations of using conventional AR, we propose to use projector-based AR for our applications. Projector-based AR is not a completely new idea, it has been proposed and used in many areas. For example, assisting human-robot interaction [23], augmenting details for cultural heritage artifacts [24], improving user's gaming experience [25], etc. Benko et al. [26] combined HMD AR display with view-dependent projection to improve user experience. However, their method needs wearable devices, which produces the same problems as we mentioned above. Also, superimposing stereoscopic views onto monoscopic projections is still a challenging work. Our method only focuses on projector-based AR technology so that these problems can be avoided. Lindlbauer et al. [27] developed a framework for combing shape-changing interface with projection mapping, while we assume that our work is performed on a plane of constant shape. Different from all these methods above, our work aims at rendering the 2D frames of objects on the correct position they projected onto the wall.

Methods for Projector-based AR. Since the projector is mobile, we need projector's math model and pose estimation. As Tatsumoto et al. [28] presented in their work, the robot can project the image to any specified location by detecting the marker placed in the environment previously. Chadalavada et al. [29] showcased their work aiming at improving the robot's ability to communicate with human by projecting internal state information through a projector. One important part of their work is to find the relationship between the real world vehicle path and OpenGL frame to render the image. While their work [28,29] required to calibrate camera-projector system ahead for a precise physical pinhole camera model, our work directly computes the homography transformation matrix between camera and projector to pass the geometry relationship between the two. Boroomand et al. [30] proposed a method that can compensate for distortion of the projected image caused by an uneven projection plane. In order to improve picture projection accuracy, we use two markers of known physical coordinates for precision control.

3 Mobile Projective AR

Our method realizes AR using a camera-projector system to ensure a consistent projection during the process,

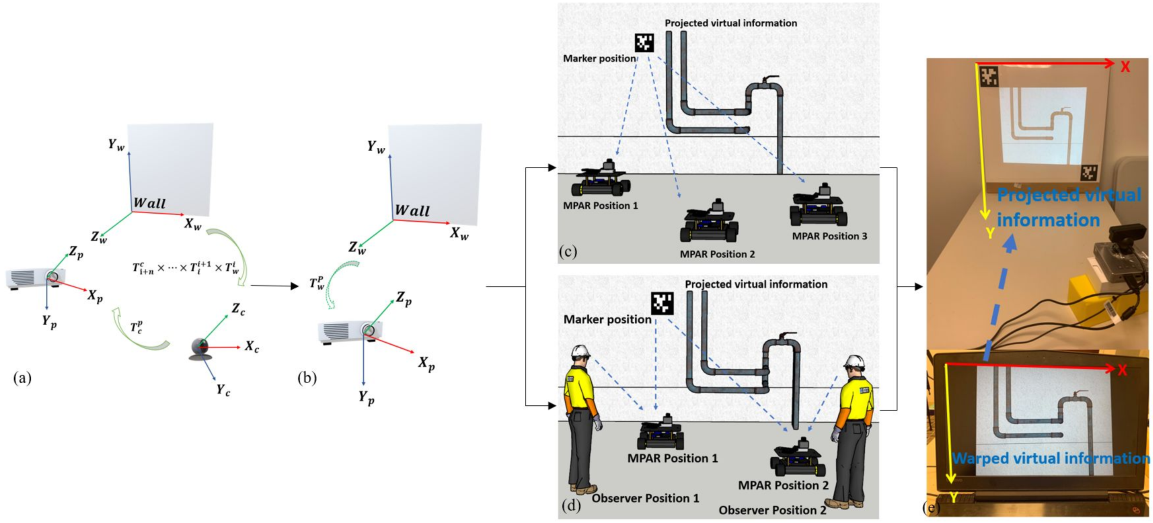

Figure 2. MPAR pipeline. (a) Pose representation and estimation. (b) Composition of projection matrix. (c) observer-independent system. (d) observer-dependent system. (e) Projection of the warped virtual information.

even if the projector might be moved due to various reasons (e.g., to enlarge/move the field of view, to make room for co-workers, etc.). Figure 2 depicts two categories of the MPAR system, one is observer-independent and the other is observer-dependent. The observer-independent MPAR system does not need to know where the observer is (we assume the position of the observer's head represents the position of the observer) while the observer-dependent MPAR system requires for the observer's position. For both systems, we first estimate and represent the pose of the projector in the world coordinate system by passing homography matrices between components in the system; then, according to the projector's pose, the projection matrix from the projector to the target projection plane can be estimated. Therefore, the observer-independent MPAR system could project the excepted virtual information onto the projection plane. For the observer-dependent MPAR system, the observer's location needs to be known before the projection phase. In this section, we will provide a general formulation of our method.

3.1 Pose Representation and Estimation

It is necessary to estimate the pose of the projector relative to the world coordinate system, so we can determine how to warp the virtual information (image or 3D model) for displaying the desired content on the projection plane without geometrical distortion. We developed a camera-projector system to estimate the pose of the projector via vision-based perception. By passing sequential transformations from the world coordinate system via the camera and other possible intermediate coordinate systems to the projector coordinate system, the pose of the projector in the world coordinate system could be calculated. The transformation from a coordinate system to b coordinate system can be represented by a matrix T_a^b. We express the transformation matrix from the world coordinate system to the projector coordinate system as:

$$T_w^p = T_c^p T_N^c \prod_{i=1}^{N-1} T_i^{i+1} T_w^1 \tag{1}$$

Here, w represents the world coordinate system, p represents the projector coordinate system and c represents the camera coordinate system. N is the total number of intermediate coordinate systems. T_i^{i+1} is the transformation from the ith intermediate coordinate system to the $(i+1)$th intermediate coordinate system. To register the position of the MPAR system, either the marker-based method or the markerless method could be used [31, 32]. Markerless AR is usually more flexible than marker-based AR for not requiring marker installation. But there are several reasons that still favor marker-based solution on several circumstances.

Why use markers? First, the markerless technology usually requires abundant visual features in the environment and there is a trade-off between precision and efficiency when applying this method to realistic job sites [33]. Second, our method is effective in indoor environments, no matter whether the projection plane has discriminative visual features or not. While marker-less AR might sometimes lose track for features. Besides, by using markers, it is more reliable to determine the location of the projection plane in the world coordinate system than without markers. Nevertheless, similar to recent works [34, 35] that integrate markers into structure from motion systems, our on-going work is combining the marker-less solution with marker-based one in MPAR system.

For marker-based AR, the relative pose can be represented by a translational vector and a rotational vector [36]. However, camera calibration is required if poses are represented in this way [32], which may cause inconvenience and complexity, thereby affecting AR application in industry.

To avoid the aforementioned drawbacks, we utilize marker-based AR. Besides, instead of using translational and rotational vectors, we choose to use homography to represent the pose, since all components in the system, such as projection plane, image plane, and makers are planar objects. Homography transformation matrix is an invertible non-singular 3×3 projective matrix which can map the corresponding points from one plane to another plane [37]. Using homography does not require camera calibration. Therefore, the pose of the projector in the world coordinate system can be represented in the form of homography:

$$H_w^p = H_c^p H_N^c \prod_{i=1}^{N-1} H_i^{i+1} H_w^1 \tag{2}$$

where we represent homography transformation between a and b coordinate systems as H_a^b. Given the pose of the projector in world coordinate system, if $\mathbf{x}_w$ are the homogeneous coordinates of a point on the projection plane in world coordinate system, then the coordinates on the projector's image plane should be:

$$\mathbf{x}_p = H_w^p \mathbf{x}_w \tag{3}$$

According to H_w^p, virtual information which needs to be projected can be converted to a warped image. By sending the warped image to the projector, the virtual information can be projected to the correct locations in the world coordinate system.

3.2 Observer-Independent MPAR

In the multi-person collaborative site, the projected information will be shared by multiple workers and designers, so the projected information should not change with the position of one person. Therefore, the previously proposed methodology, equation 3 could be used for the displaying purpose.

3.3 Observer-Dependent MPAR

In contrast to observer-independent MPAR, the projected content of an observer-dependent MPAR system is related to the observer's position. This feature is important when the worker or designer on the site is moving while observing a 3D virtual model. To establish an observer-dependent MPAR system, either static projector(s) or mobile projector(s) can be used.

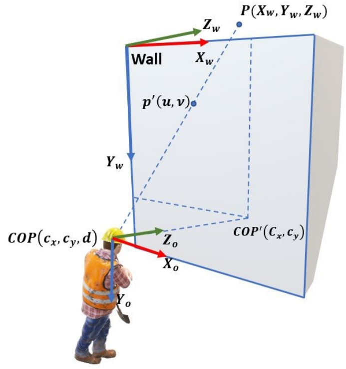

Figure 3. Illustration for computing a projected point in the observer-dependent MPAR.

For the observer-dependent MPAR system using static projectors, the pose of the projector relative to the world coordinate is known. Therefore, the virtual information can be projected directly without computing the series of homography transformation matrices. We can only focus on the impact of human location on the overall system. Equation 4 links the three-dimensional coordinates of the object to the corresponding projected two-dimensional coordinates by the observer's location.

$$s \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \underbrace{\begin{bmatrix} d & 0 & c_x & 0 \\ 0 & d & c_y & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}}_{\text{projective}} \underbrace{\begin{bmatrix} 1 & 0 & 0 & -c_x \\ 0 & 1 & 0 & -c_y \\ 0 & 0 & 1 & d \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{\text{world to observer}} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} \tag{4}$$

Figure 3 establishes the world coordinate system and the observer coordinate system. The observer's location COP, the virtual point's location P and its projection on the wall P' have also been defined. For proper projection, we first convert the coordinates of the object from the world coordinate system to the observer coordinate system. For this conversion, since the corresponding coordinate axes of the two coordinate systems have the same direction, the rotation matrix is a 3×3 identify matrix; the translation vector is $(-c_x, -c_y, d)$, related to the observer's location. To apply the transformation matrix to the homogeneous coordinates of $P(X_w, Y_w, Z_w)$, the rotation and translation matrix should be combined as the world to observer matrix in equation 4. Then the object's coordinates $P'(u, v, 1)$ in the world coordinate system plane can be obtained by multiplying the projective matrix in equation 4. s is a scaling factor.

The observer-dependent MPAR system using mobile projectors is complicated and comprehensive in taking

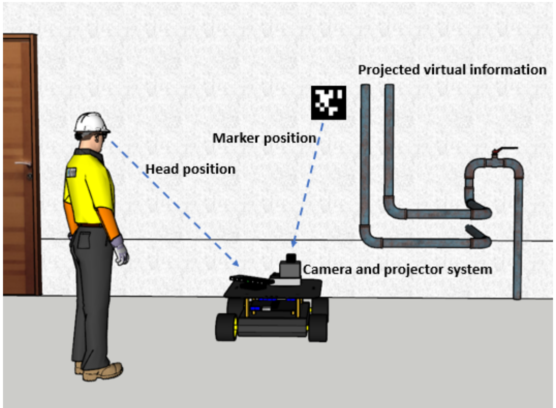

Figure 4. Illustration of observer-dependent MPAR.

both observer's location and projectors' mobility into consideration. The methodology of this system can be realized as a combination of the aforementioned methodologies. Figure 4 shows the schematic of the observer-dependent MPAR system. Knowing the position of the observer (COP), the coordinates of the virtual point being projected onto the projection plane P' can be calculated by equation 4. Then according to equation 3, coordinates of P' on the warped image can be calculated.

4 Applications

It is important that designers and workers can see building/facility information in the exact location during the construction process. For example, in the maintenance or inspection process, workers can evaluate the quality of the building by comparing the appearance of the on-site building with the as-designed building information projected onto the site. Based on the aforementioned MPAR methodology, our first task is to project as-designed building/facility information to where they are located.

Our task 2 is to detect the object behind the wall, visualize and save the detected RF signal based on the framework of MPAR methodology. In practice, workers can set up the markers in an unknown construction site for renovation work. After settling down the MPAR system, they should be able to employ the Walabot to detect the hidden objects and visualize them in real time. Moreover, they can save the detected signal to BIM database for future information retrieval. Task 2 is a prototype for such work, and its result can be seen in Figure 1.

Since in last section, we have provided a general formulation of our proposed method, in this section, we will show two applications which realize our method.

4.1 Projection of As-Designed Building Information

Some assumptions should be made before the implementation of task 1. First, it is reasonable that we have access to as-designed building information and its location in the world coordinate system. Also, since our pose estimation method is based on detecting optical markers, the projection area is within the control range defined by markers, so the physical coordinates of the building information that our task can project need to be within the control area.

System Setup. For computing homography matrix, AprilTag, a robust visual fiducial system [38] is utilized to detect correspondences in two coordinate systems [39,40]. By placing markers on the wall, the world coordinate can be defined. As Figure 5 shows, a RGB camera is fixed on the ultra short throw projector. Also, a laptop is utilized as a mobile workstation for computing homographies and displaying the virtual information.

Related Transformations:

Wall to Camera. For this part, we first set up the two markers on the wall, as can be seen in Figure 5, to define the world coordinate system, which is a 2D coordinate system on the wall plane. Then we measure the physical coordinates of four corners for each marker. Also, the on-board camera captures an image which contains the two markers. The image coordinates of eight corners can be automatically measured. Then the homography from world coordinate system to the camera's image coordinate system H_w^c can be calculated using Direct Linear Transformation (DLT).

Camera to Projector. In addition to capturing the physical markers on the wall, the RGB camera is also set up to capture the projected marker. An image of a marker is sent to the projector to make it being projected on the wall. Then the RGB camera takes an image of the projected marker on the wall. The corners of the projected marker are automatically measured in the captured image and the input image. According to the corresponding corners, homography from camera's image coordinate system to projector's image coordinate system H_c^p can be calculated.

Wall to Projector. After obtaining H_w^c and H_c^p, H_w^p can be calculated according to equation 2. Then the warped image sent to the projector can be obtained according to equation 3.

Result. As we can see in Figure 5, suppose the plumbing is located in the control area defined by the markers, though the projector is moving, the projected information remains at the same specified location.

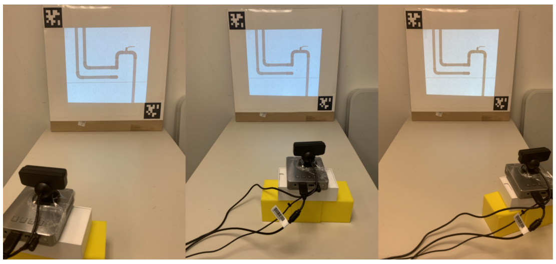

Figure 5. Observer-Independent MPAR for as-designed building information

4.2 Projection of Occluded Building Information

Specific Image Warping Representation. Unlike the previous application, which needs to find homography transformation from world coordinate system to projector coordinate system, this application aims to project the sensed RF image to the correct location on the wall. Therefore, homography from the sensed image coordinate system to the projector's image coordinate system H_i^p needs to be calculated:

$$H_i^p = H_c^p H_s^c H_i^s \quad (5)$$

H_c^p, H_s^c, H_i^s represent the homography transformation from camera's image to projector's image, Walabot sensor's coordinate system to camera's image and sensed RF image to Walabot sensor's coordinate system respectively. To better visualize the detected RF image, we rendered a circle, centered on the location of object being detected, on the 21×21 pixel sensed RF image. According to H_i^p, we could warp the RF image such that it can be projected properly on the projection plane.

Since the projector's pose is changing during the projection process, we should warp the image of the previous frame to align with the projector's pose of the current frame and fuse all images together to get a global image for projection.

System Setup. In addition to the camera-projector system used in the previous application, Walabot, a handheld 3D-imaging device was utilized for detecting the RF signal of the object behind the mock wall. Since it is difficult to directly detect the pose of the Walabot sensor plane, we attached a marker on the Walabot to detect its position.

Related Transformations:

Image to Sensor. The homography transformation matrix H_i^s is pre-defined since we specified the physical sensing arena in the sensor coordinate system and image size in the digital image coordinate system. We can calculate H_i^s by using the corresponding four corners in both two coordinate systems.

Sensor to Camera. To compute the transformation matrix between the sensor coordinate system and the projector coordinate system, we attached an optical marker on the opposite side of the sensor plane, whose center coincides with the surface's center in z axis, as can be seen in Figure 1. By capturing the four corners of the marker, we could compute the homography H_t^c between the tag and the RGB camera. For the transformation between the sensor plane and the marker plane, we can easily measure the the thickness of Walabot, which represents the translational vector between sensor plane and tag plane. Since homography transformation matrix does not contain the translational information explicitly, we need to use affine matrix for geometry transformation. By decomposing the homography transformation matrix H_t^c with the RGB camera's intrinsic matrix, we can obtain the affine matrix which contains the rotational and translational information between the tag and the camera; adding the translational vector allows us to get the affine transformation matrix between sensor plane and the RGB camera. Then we can compose the homograhpy matrix H_s^c with the camera's intrinsic matrix.

Camera to Projector. This part of implementation is the same as the previous application.

With these homogaphy matrices obtained, we could calculate the homography transformation between project the warped image of each frame onto the projection plane properly.

Two Frame Image Fusion. Since the projector is moving during the scanning process, we need to fuse the previous frame image to the current frame image such that H_i^p is always representing the current homography transformation matrix between image coordinate system and projector coordinate system. The homography between two frames can be calculated by solving DLT problem using the optical markers' points captured by the RGB camera in two frames. After knowing the homography transformation matrix between two frames, we can warp the previous image using equation 3 and fuse it with the current image.

Result. By sending the fused image to the projector, we can visualize the water pipe behind the mock wall. As can be seen in Figure 1, our result shows that even the projector's pose changed during the scanning process, our system could still augment the occluded water pipe consistently.

5 Conclusions

In this paper, we proposed MPAR, a camera-projector AR system which ensures a consistent projection even when the device might be moving during the AR process. In our two applications, by composing a series of homographies modeling poses between components in the system, it is possible to warp the virtual information in the projector coordinate system and display it on the projection plane as desired.

Limitations and Discussions. There are some limitations in our proposed method. Limited by the image brightness of the projector, the result of our method might be affected by the sunlight outdoors. Also, since our method uses optical markers for detecting feature points, it might cause extra workload for setting up these markers. The method might even become invalid in a large-scale scenario due to the inability to detect the markers.

Another limitation is that our MPAR system does not provide an as immersive environment as helmets/goggles (see-through based AR). Yet we believe that the restricted field of views will cause safety concerns for the construction industry, which could be a more serious problem compared to the less immersive user experience.

Future Work. Some future work needs to be done to produce a more general and reliable MPAR system. One work is to calibrate the projector to obtain the intrinsic matrix, thus we could know the pose of the projector as long as we know the extrinsic matrix of the projector. This frees us from acquiring the image of the projected marker. Also, we believe that by projecting the virtual information on uneven surfaces using 3D cameras, the MPAR system could be applied to more scenarios. Another important work we need to conduct is quantitative evaluation. It is important to evaluate how accurate our method is, and we should also explore some possible factors that might affect the accuracy of our method.

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