Calibration of automotive augmented reality head-up displays (AR-HUDs) using a consumer grade mono-camera

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Mercedes-Benz
Das Beste oder nichts.

Outline

Introduction

- AR-HUD
- Demand for calibration
- State-of-the-art

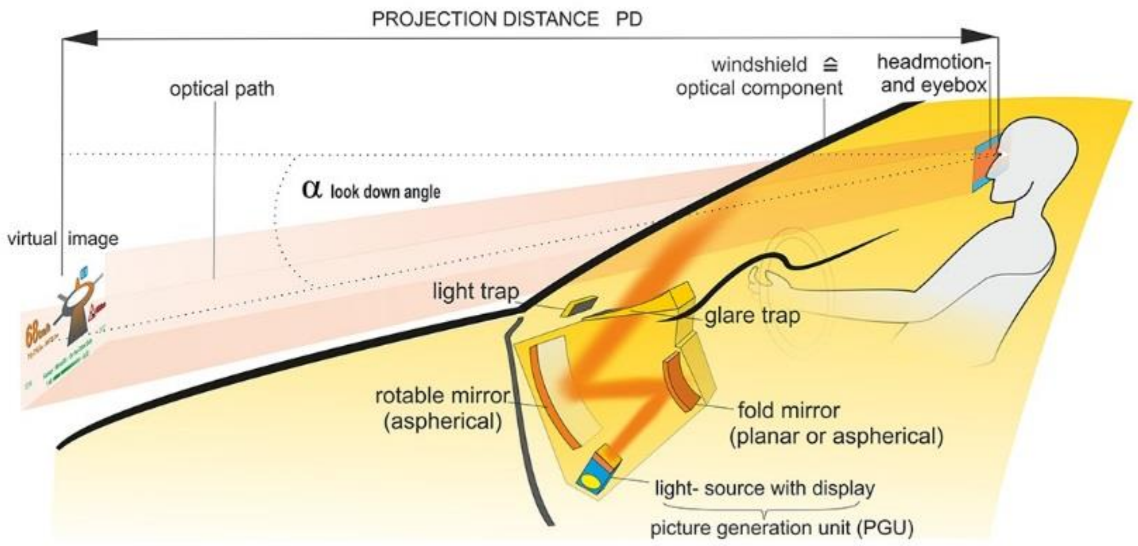
Scheme & experiment

- Pinhole-model
- Setup
- Measurement

Data processing & results

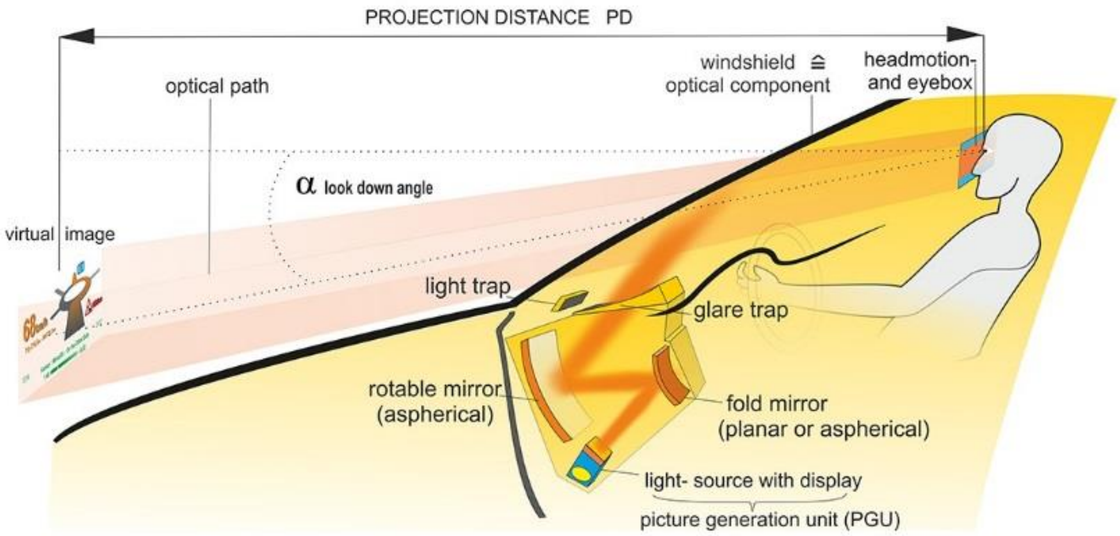
- Validation & evaluation
- Warping maps & interpolation

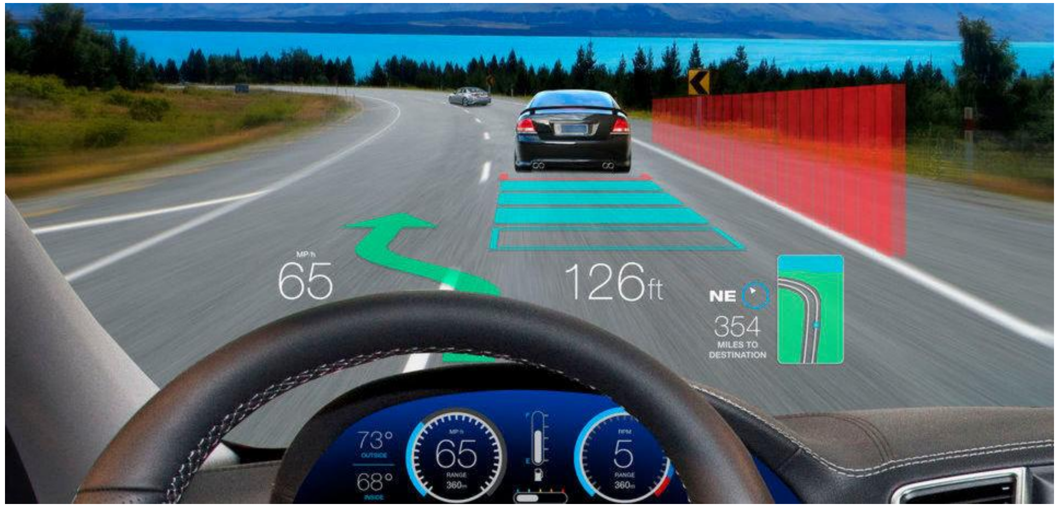
Discussion



Source: https://www.arburg.com/fileadmin/redaktion/sonstiges/fachvortrag_technologie-tage_2017_starke_partner-continental_handout_en.pdf

AR-HUD





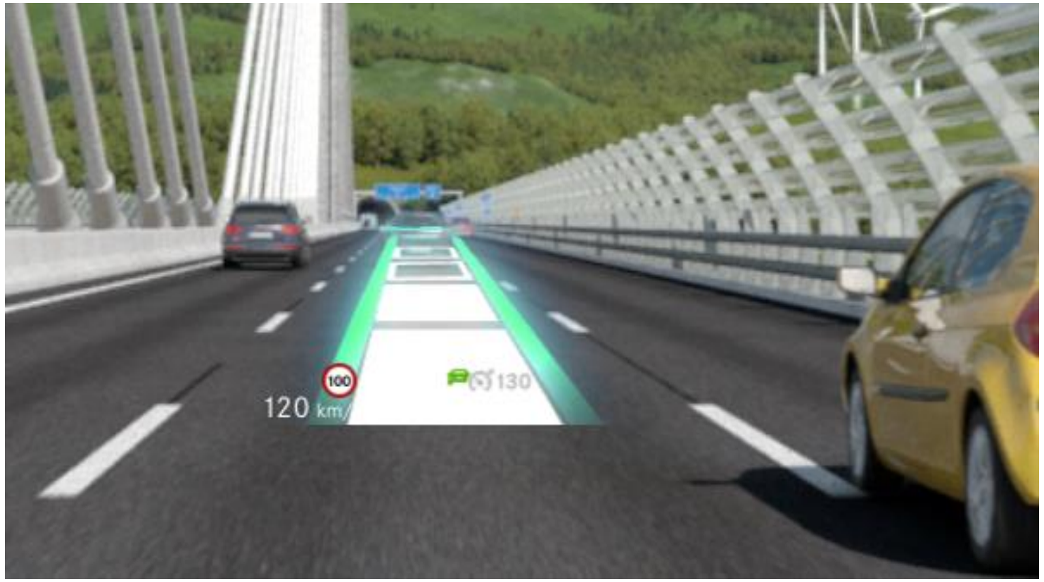
Source: http://www.ti.com/dlp-chip/automotive/applications/applications.html

An AR-HUD can visualize virtual objects as if they were merged with the real scenes.

The driver can receive information about navigation, driving conditions, and other content.

Dashboard or video screen are replaced. More concentration on the traffic.

Demand for calibration



Augmentation relies on precise 2D-3D correspondences
- 2D virtual objects & 3D real positions

An uncalibrated AR-HUD generates misaligned virtual image -> biased navigation

Main causes for inaccurate augmentation: biased physical model & optical distortion

State-of-the-art

General idea

- Acquisition of enough accurate 2D-3D correspondences in FOV of AR-HUD
  - 2D points in virtual image & 3D points on a real target

Approaches

- Pinhole camera model -> intrinsics (K), extrinsics (R, t) [1, 3]
- Direct mapping -> virtual image (u, v) – camera image (x, y) [2]
- Regression model for distortion correction -> further suppress reprojection errors [1-3]

Feature\Approach	Pinhole camera model	Direct mapping
Access to intrinsics/extrinsics	Yes	No
Calibration of head tracker	Yes	No
Pure data-driven	No	Yes
Vulnerable to asymmetric optical distortion	Yes	No

[1] F. Wientapper, H. Wuest, P. Rojtberg, and D. Fellner, "A camera-based calibration for automotive augmented reality head-up-displays," in 2013 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), 189–197 (2013).

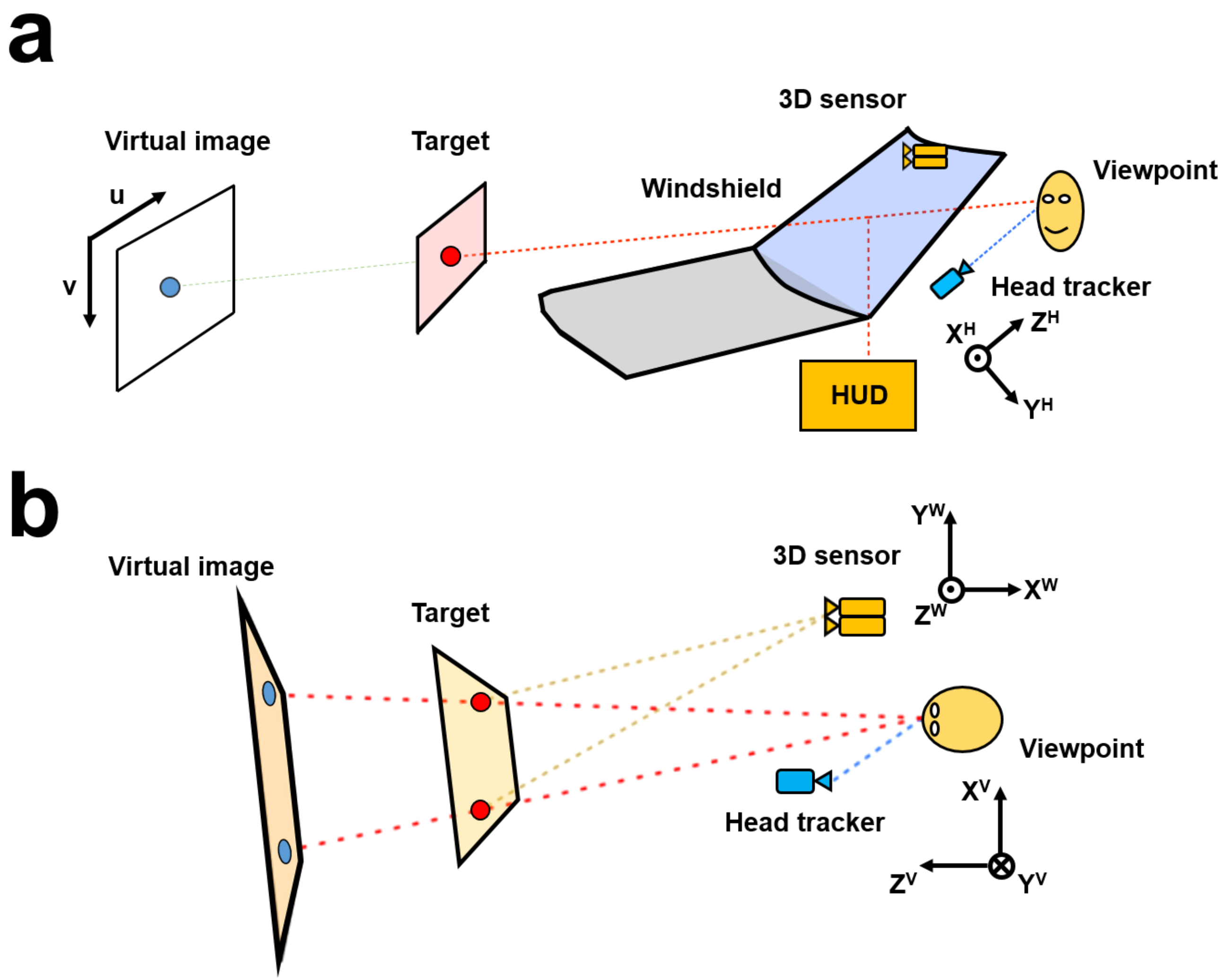
[2] K. Ueno and T. Komuro, "Overlaying navigation signs on a road surface using a head-up display," in 2015 IEEE International Symposium on Mixed and Augmented Reality, 168–169 (2015).

[3] N. Deng, Y. Zhou, J. Ye, and X. Yang, "A calibration method for on-vehicle AR-HUD system using mixed reality glasses," in 2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), 541–542 (2018).

Scheme

Involved devices

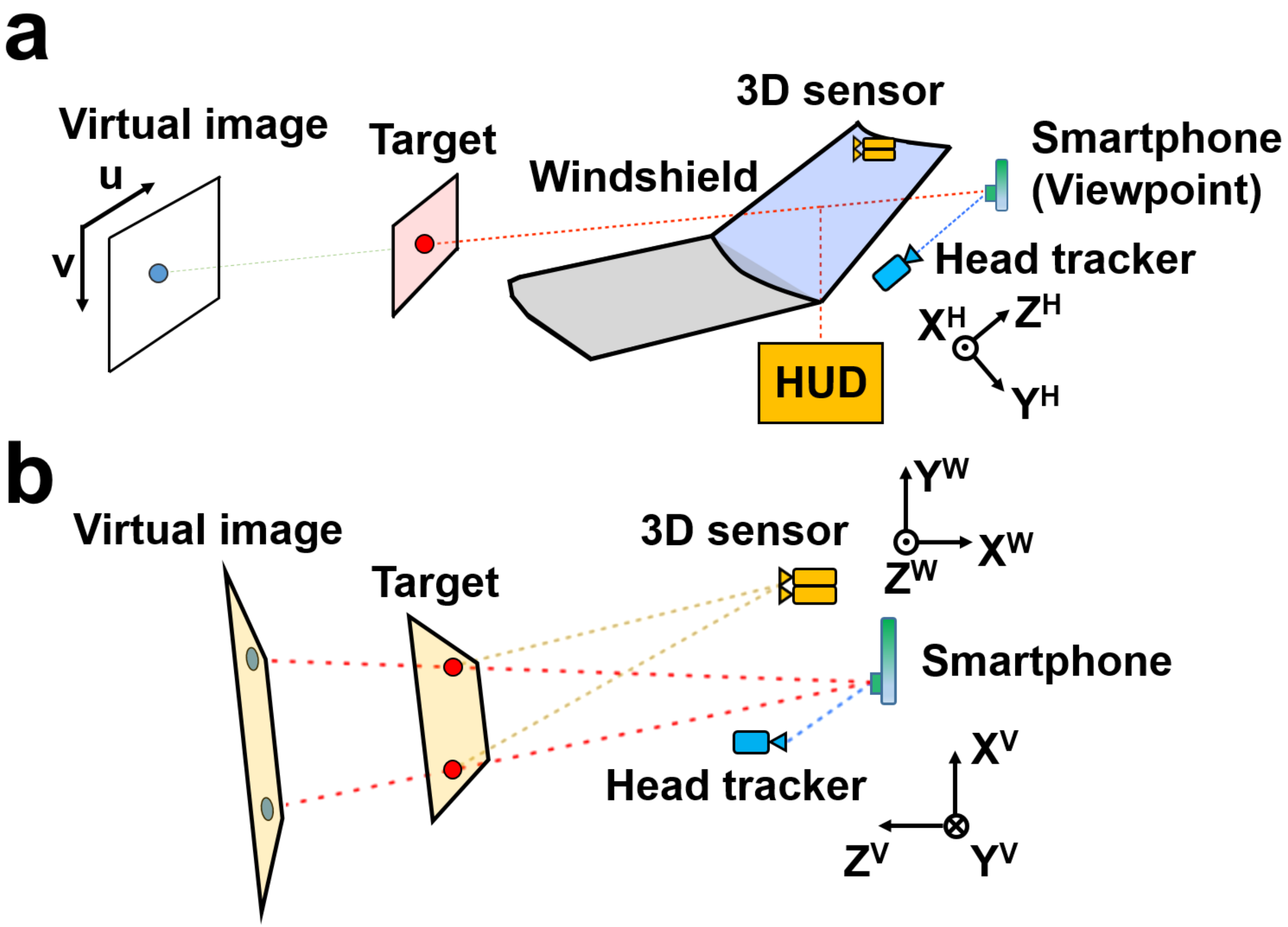
- HUD module
- 3D sensor (e.g. stereo camera)
- “Eye”, i.e. viewpoint (VP)
- Head tracker
- Target
- “Eye” moving devices



Scheme

For automatic implementation

- HUD module
- 3D sensor (e.g. stereo camera)
- Mono-camera like a smartphone
- Head tracker (edited to track the mono camera)
- Target
- Mono-camera moving devices



Math model

$$w \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \underbrace{\begin{bmatrix} f_u & s & u_0 & 0 \\ 0 & f_v & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}}_{\text{intrinsics}} \underbrace{\begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{\text{extrinsics}} \begin{bmatrix} X^w \\ Y^w \\ Z^w \\ 1 \end{bmatrix}$$

Perspective projection for HUD imaging, including linear transformations between different coordinate systems.

Distortion model tells us how to correct the image after perspective projection.

Input data

- 3D points on target *(X, Y, Z)*
- 2D points on virtual image *(u, v)*

Output data

- Intrinsic matrix *K*
- Extrinsic matrix *[R | t]*
  - Roll, pitch, yaw angles
  - Translation (eye position)
- Transformation: head tracker -> world
- Distortion correction data

Setup

Smartphone

– Huawei P10 Lite (later Apple iPhone 7 Plus)
– Pre-calibrated

Mouting & moving device

– Physik Instrumente Moving Stages (2D)
– 100 mm/s velocity & 0.5 µm resolution

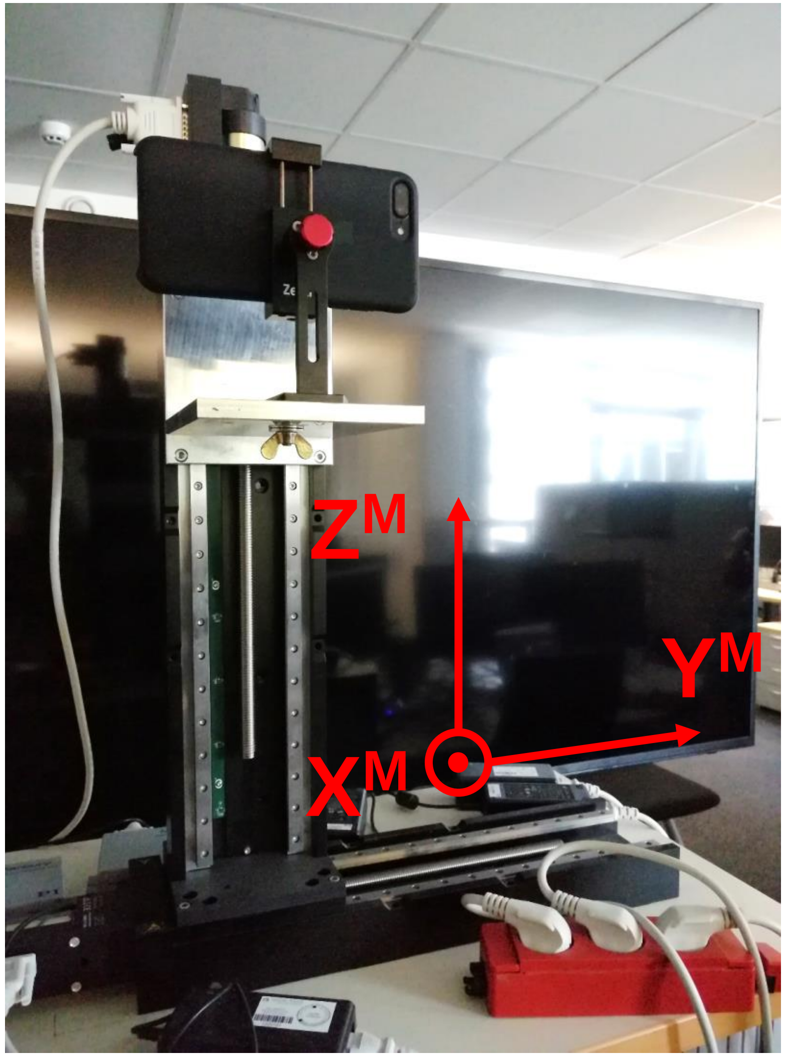
3D sensor & head tracker

– 2 calibrated ZED Camera (StereoLabs)

Source: https://www.stereolabs.com/zed/

Chessboard pattern

– Displayed on a Samsung screen (UE65MU6199UXZG, 140 cm × 80 cm)

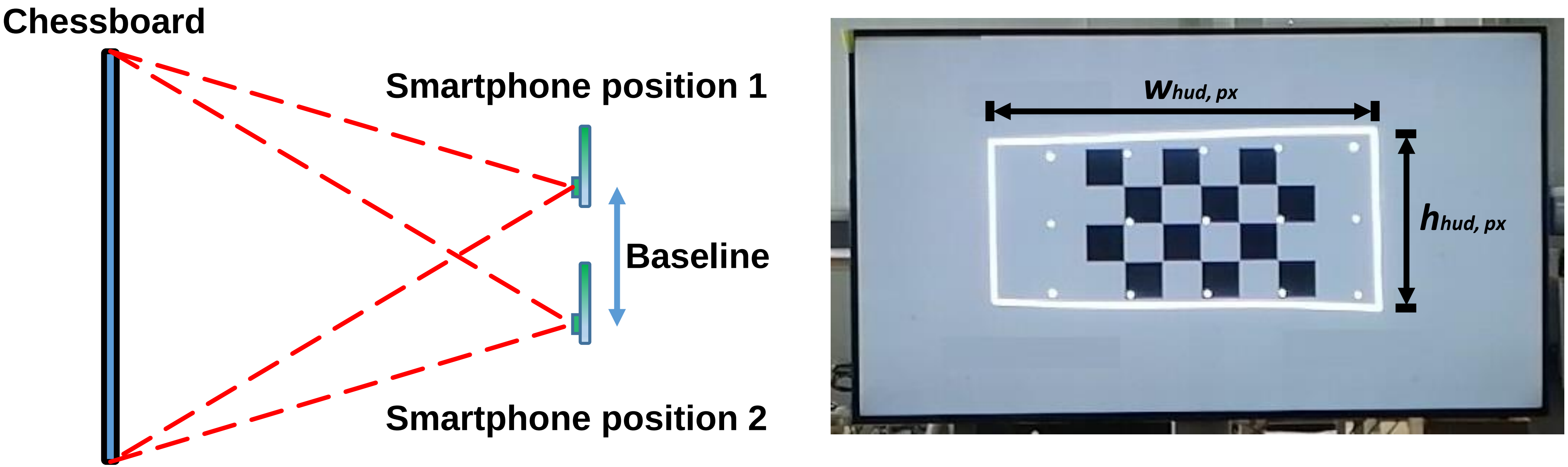


Measurement

View-independent intrinsic matrix

a

b

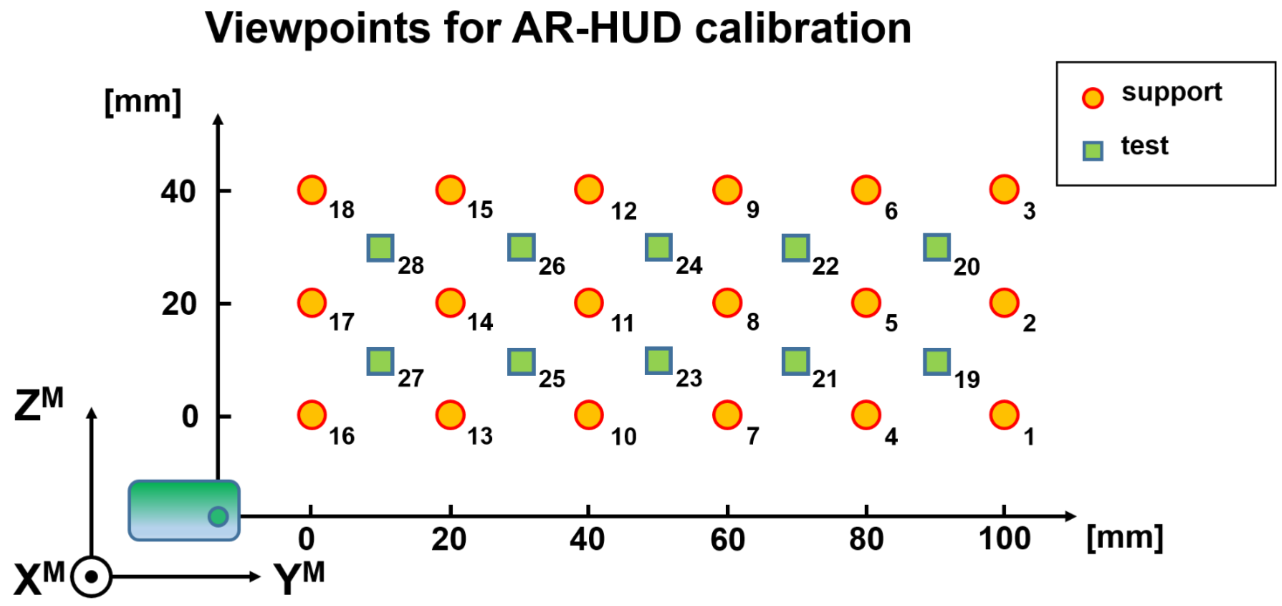


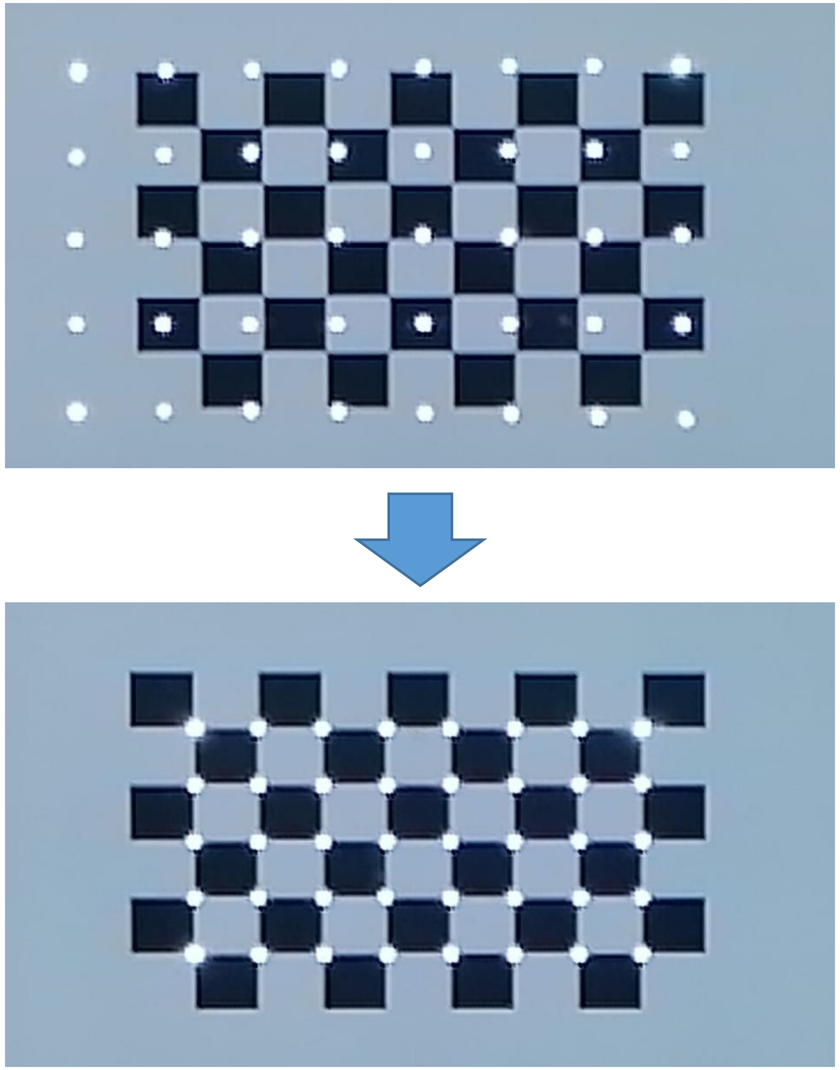
$$f_u = d \cdot \frac{w_{hud,px}}{w_{hud}}\,, \quad f_v = d \cdot \frac{h_{hud,px}}{h_{hud}}$$

Assuming rectangular pixel (no skew) and the principal point falls onto the image center.

Measurement

View-dependent extrinsic matrix





Operation

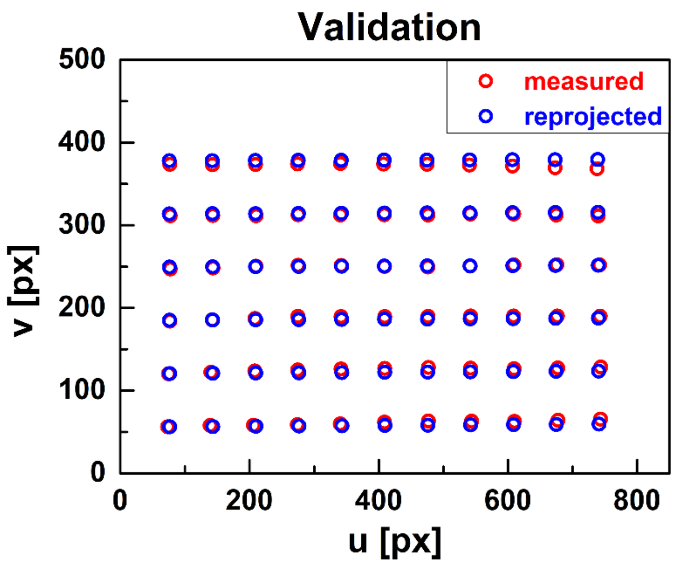
– Automatic shifting of 2D virtual points to 3D control points
– Repeat for multiple viewpoints and target distances

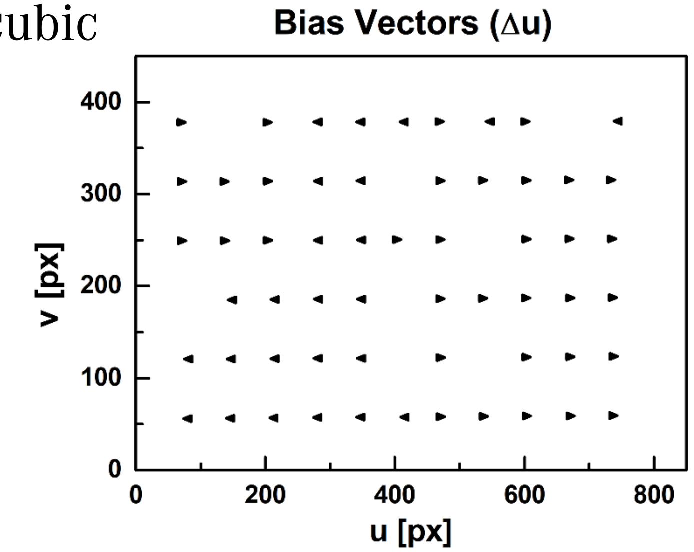
Data processing

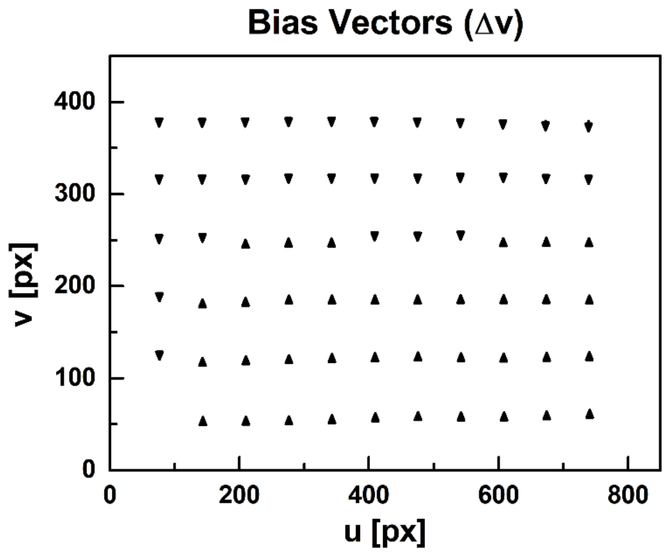
Validation & warping maps

At each viewpoint, we reproject the 3D control points onto 2D virual image

- Comparison between measured & reprojected virtual points
- Generation of bias vectors
- Generation of warping maps using bicubic interpolation







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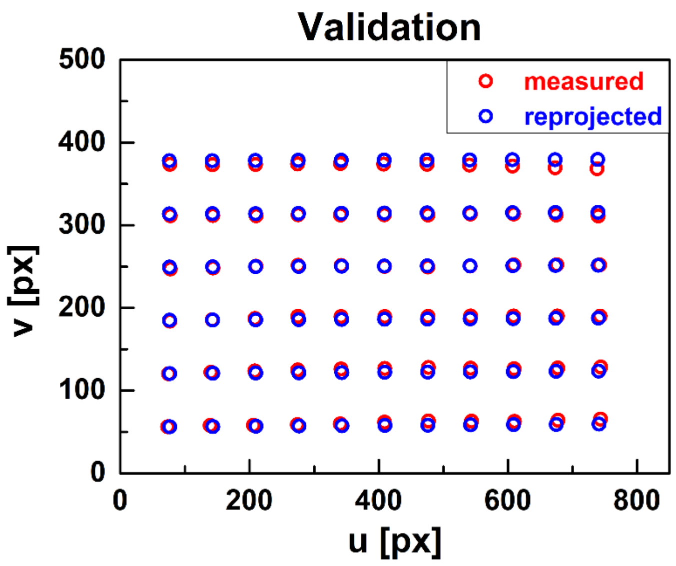
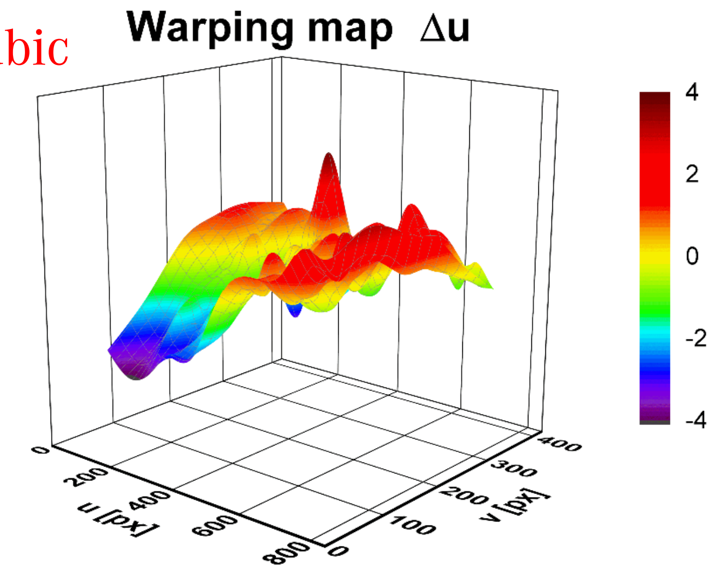
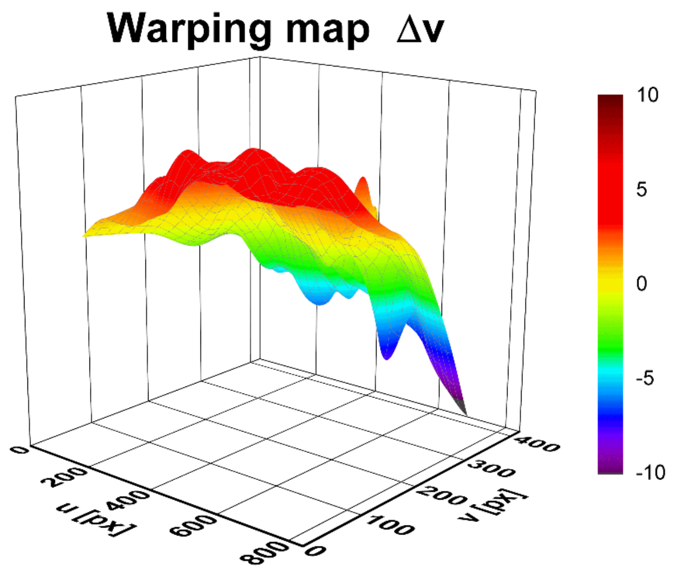


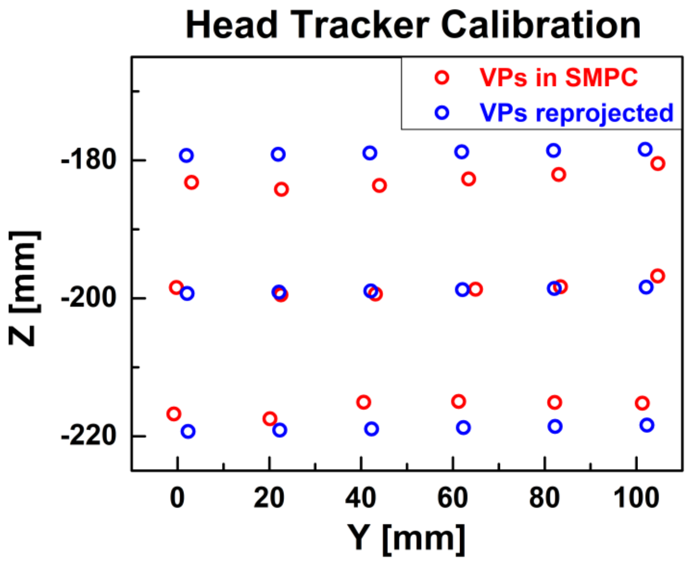




Head tracker & interpolation

Calibration of head tracker

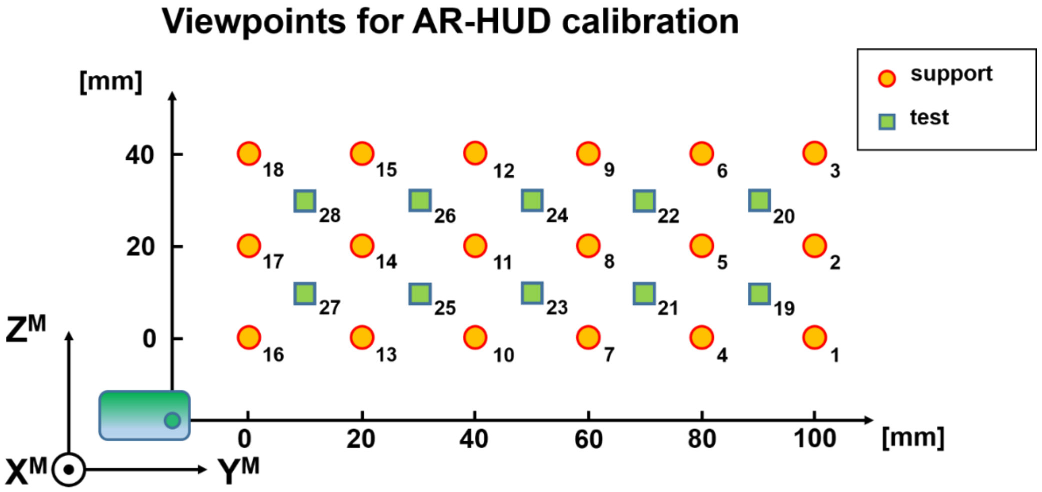
$$\begin{bmatrix} X_v^W \\ Y_v^W \\ Z_v^W \\ 1 \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{t} \\ 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$



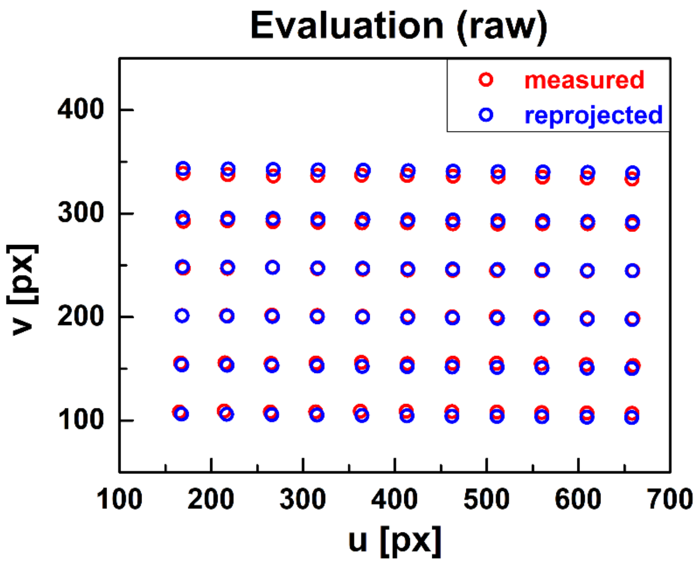
Interpolation of extrinsics

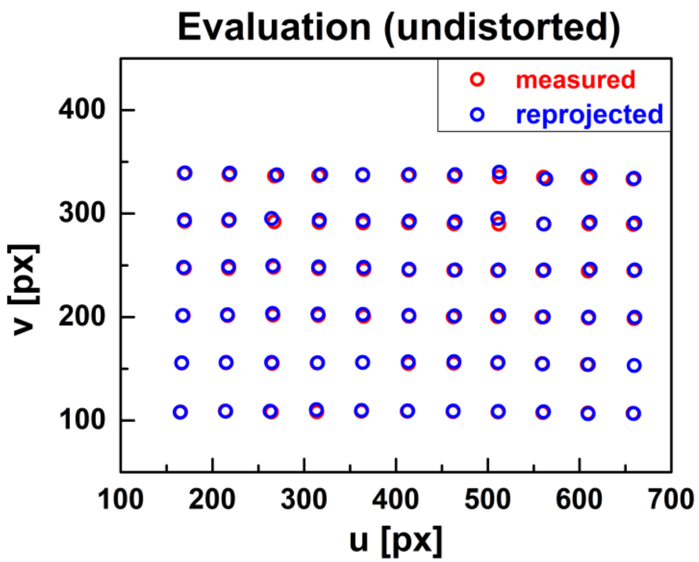
For test viewpoints, we compute their extrinsic matrices by interpolation of support ones

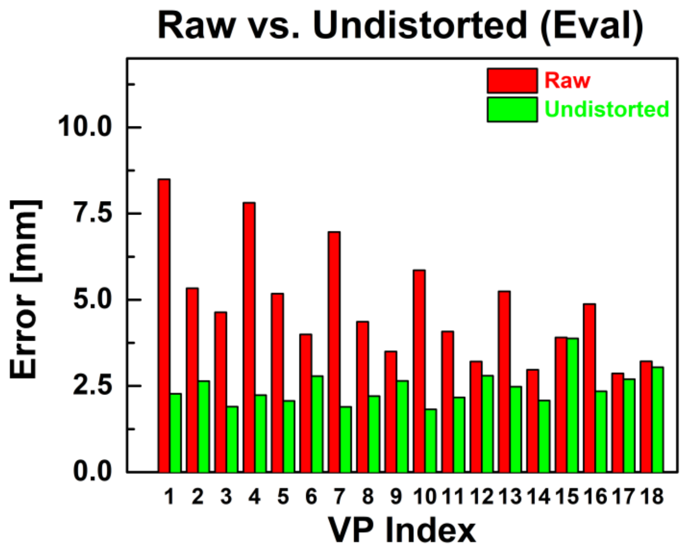
- 6 degree of freedoms
- Prefer to use Rodrigues rotation vectors

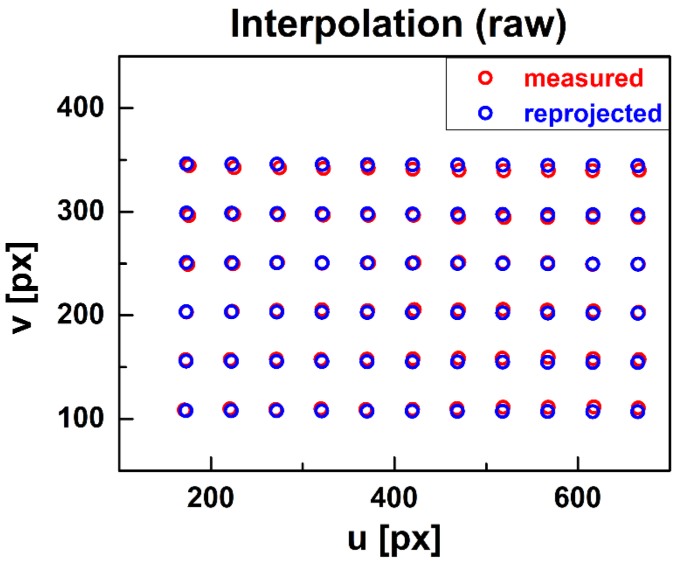


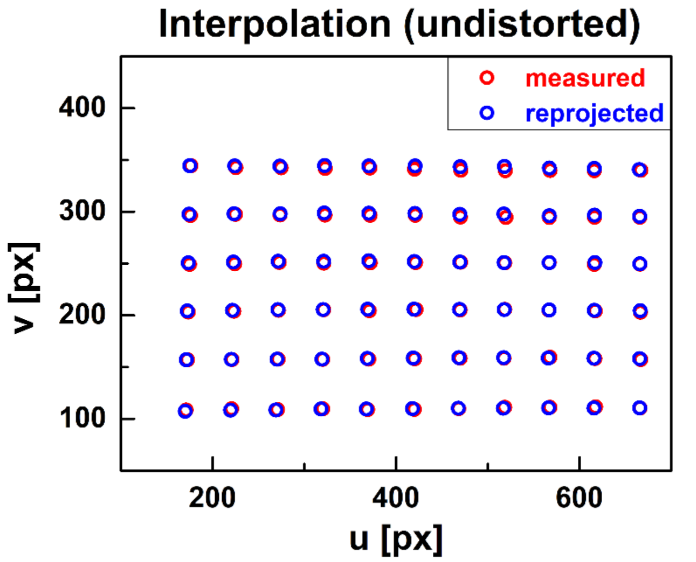
Evaluation @ multiple viewpoints

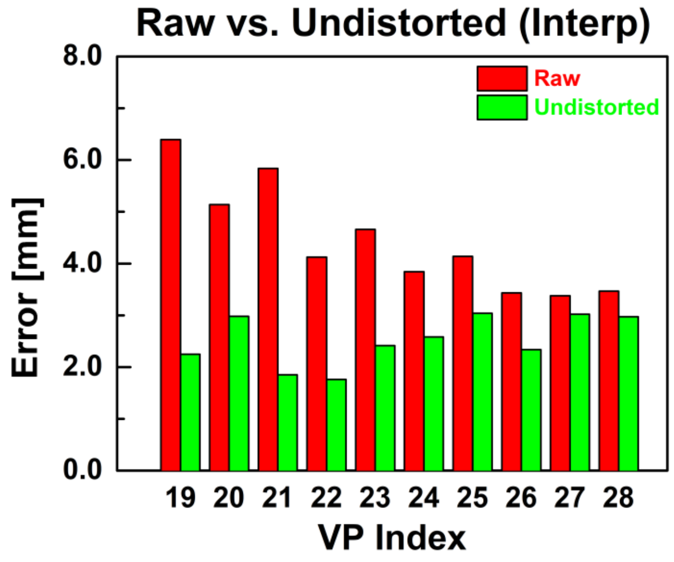












Discussion

Advantages

- Utilization of devices equipped in the vehicle
- Less dependent on specific extra components
- Consideration of multiple viewpoints via interpolation
- Calibration of the head tracker
- Warping map is a more intuitive distortion model

Points to improve

- More rigorous determination of intrinsic parameters

Thank you!