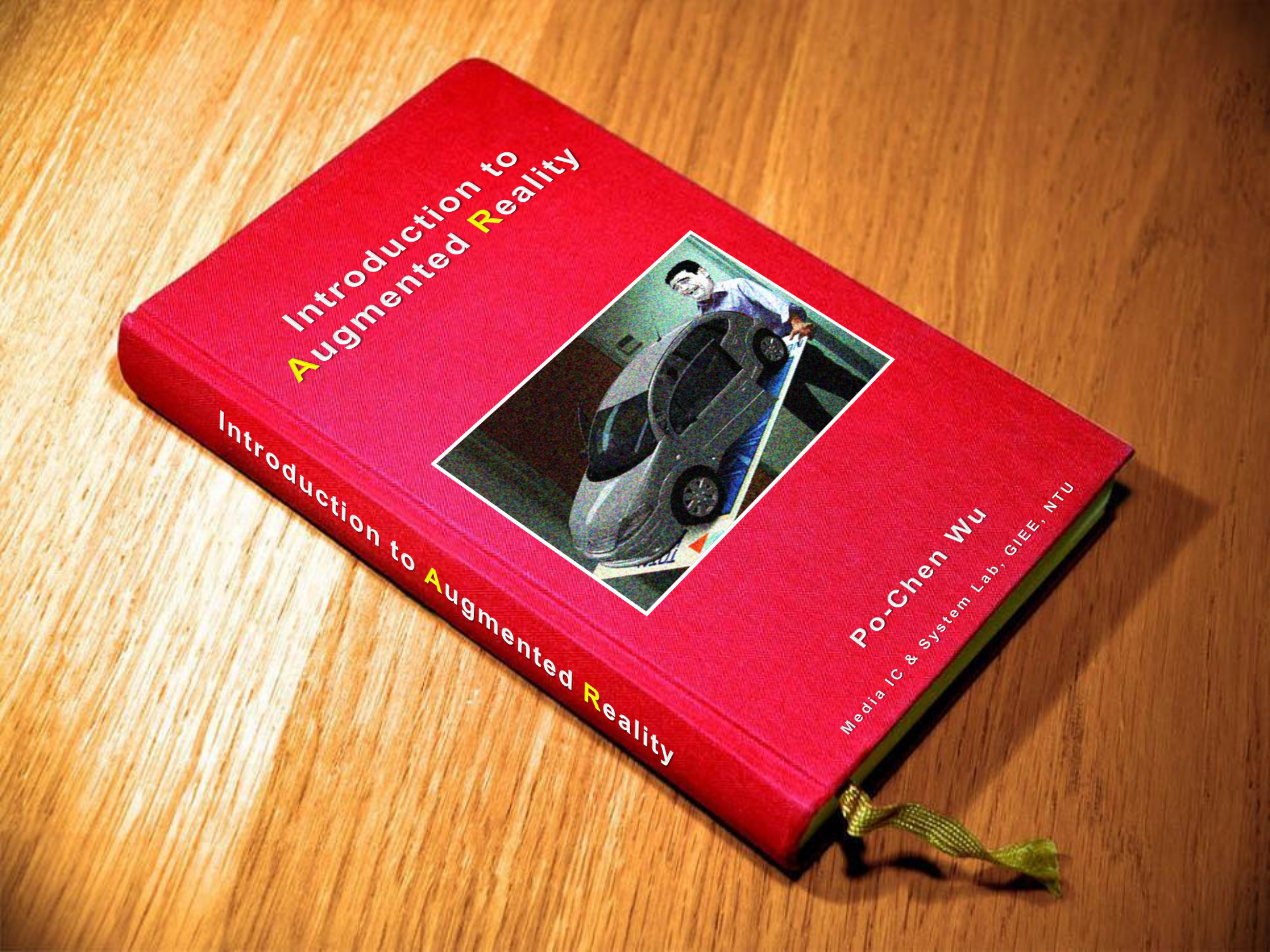

Introduction to
Augmented Reality
Introduction to Augmented Reality
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Outline

- Introduction
- System Overview
- Camera Calibration
- Marker Tracking
- Pose Estimation of Markers
- Conclusion

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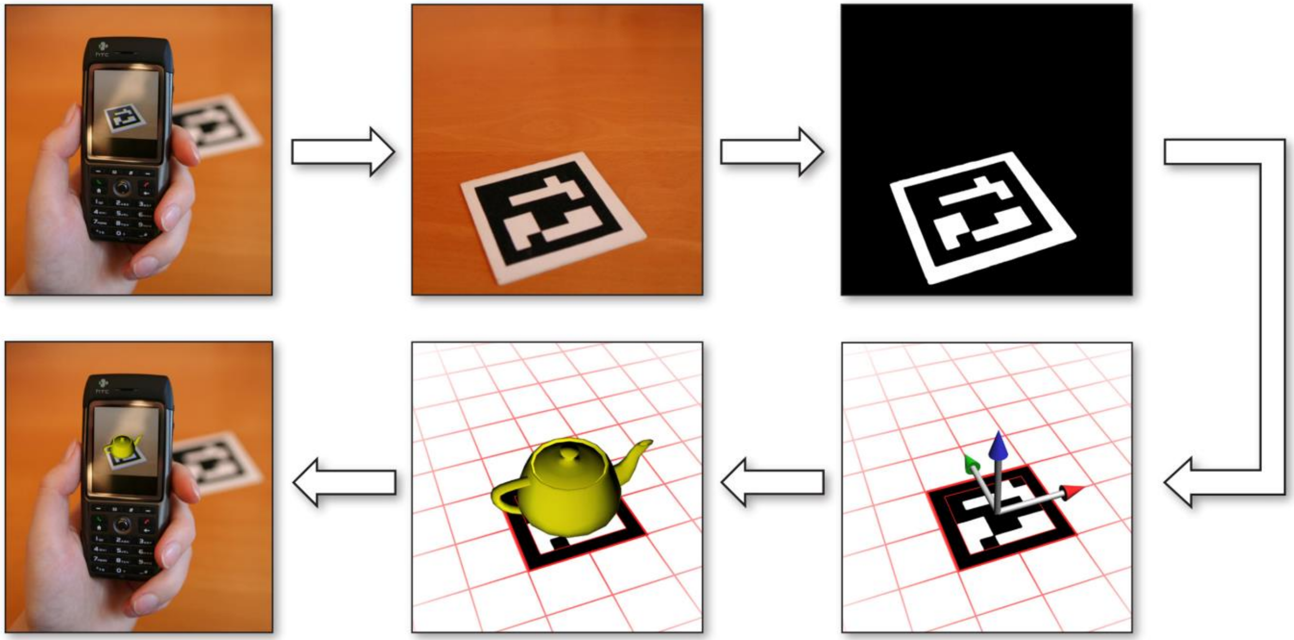
Introduction

- R. T. Azuma[1] define an Augmented Reality (AR) system to have the following properties:
  1) Combines real and virtual
  2) Interactive in real time
  3) Registered in 3-D

[1] Azuma, Ronald T. "A survey of augmented reality." Presence 6.4 (1997): 355-385.

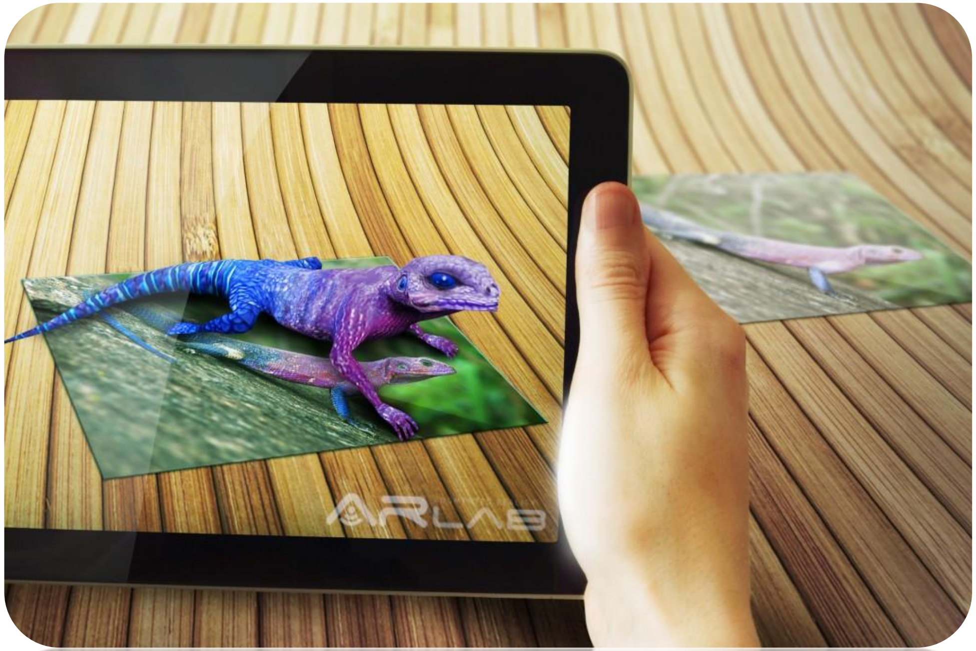
Marker-based AR

- Basic workflow of an AR application using fiducial marker tracking:



Markerless AR

- Markerless augmented reality systems rely on natural features instead of fiducial marks.



Features

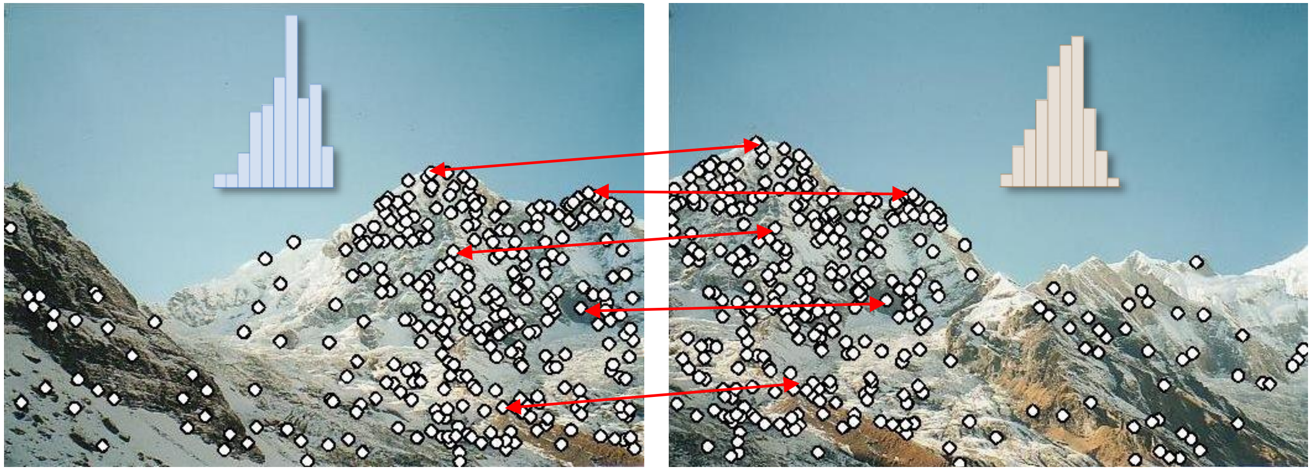
- Also known as interesting points, salient points or keypoints.
- Points that you can easily point out their correspondences in multiple images using only local information.

Desired Properties for Features

- Distinctive: a single feature can be correctly matched with high probability.
- Invariant: invariant to scale, rotation, affine, illumination and noise for robust matching across a substantial range of affine distortion, viewpoint change and so on. That is, it is <u>repeatable</u>.

Components

- Feature detection locates where they are.
- Feature description describes what they are.
- Feature matching decides whether two are the same one.



Detectors & Descriptors

- Feature detector:
  - Harris, Hessian, MSER, **SIFT**, **SURF**, FAST, etc.
- Feature descriptor:
  - **SIFT**, **SURF**, DAISY, BRIEF, FREAK, etc.

Another Markerless AR

- Complete registration with GPS, inertial sensors, and magnetic sensors.

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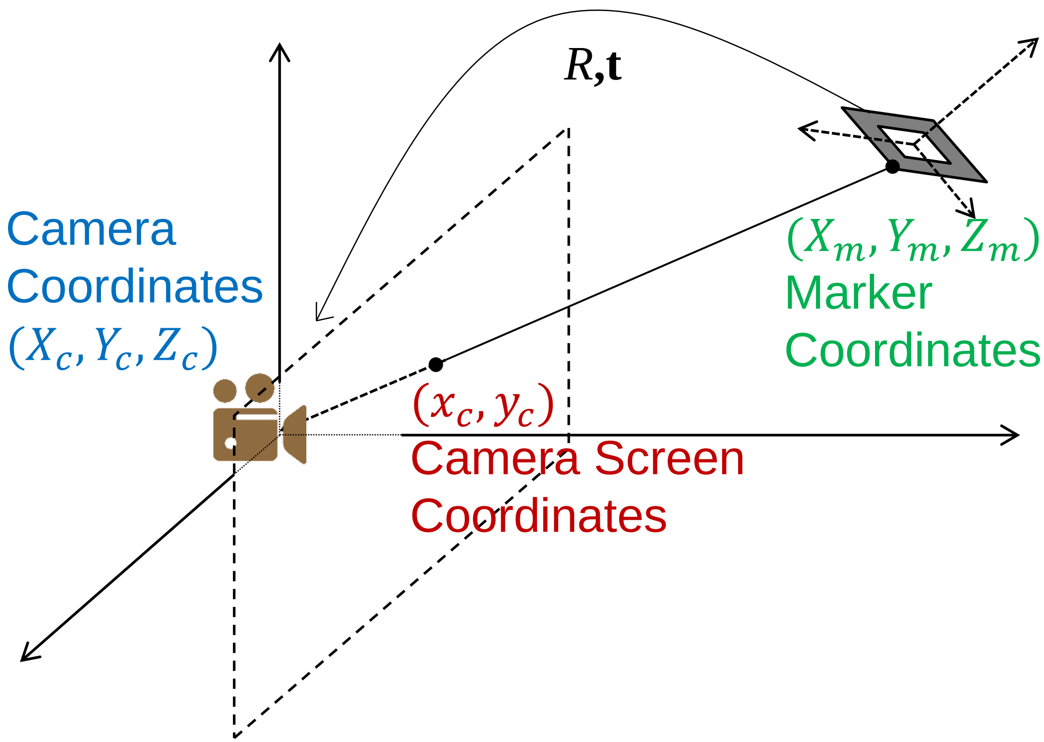
System Flow

Camera Calibration → Marker Tracking → Pose Estimation → Rendering



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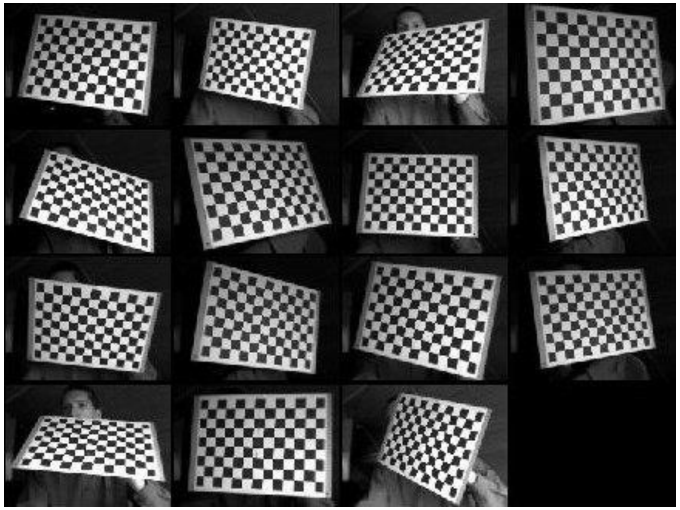
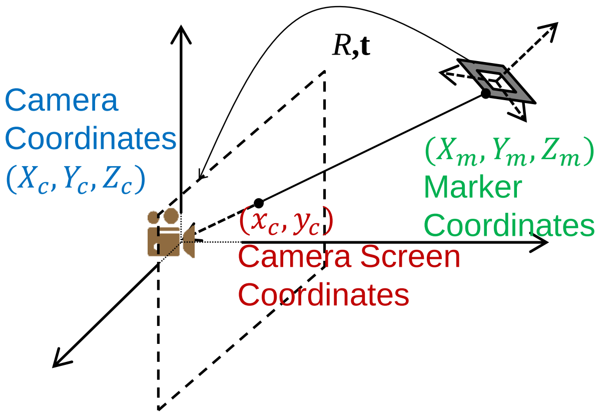
Camera Calibration (1/6)

- We use a simple cardboard frame with a ruled grid of lines for the camera calibration.
  - Relationships between the camera screen coordinates and the camera coordinates can be known.



Camera Calibration (2/6)

- The relationships among the camera screen coordinates (x_c, y_c), the camera coordinates (X_c, Y_c, Z_c) and the marker coordinates (X_m, Y_m, Z_m) can be represented as below:



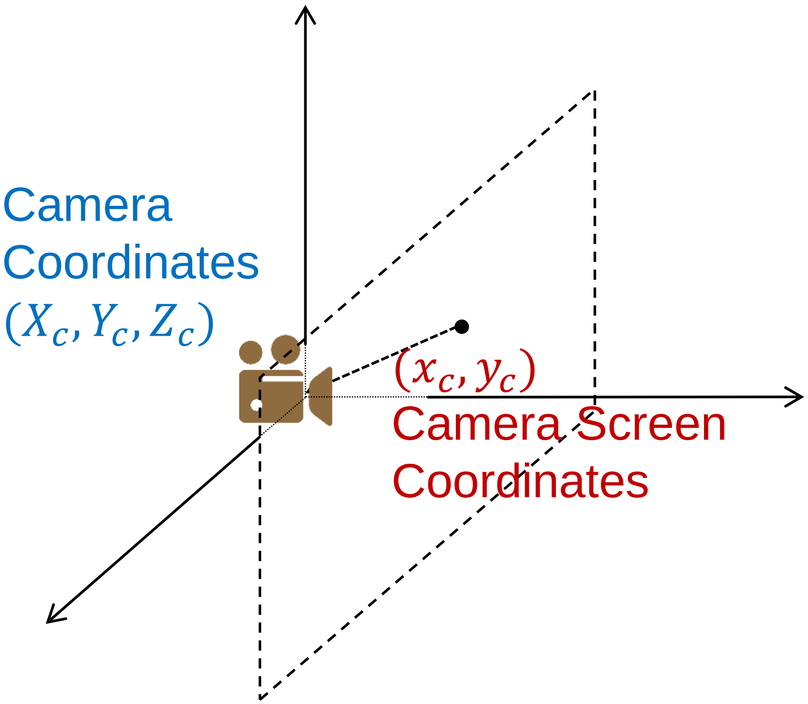
$$\begin{bmatrix} hx_c \\ hy_c \\ h \\ 1 \end{bmatrix} = \mathbf{P}\begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} = \mathbf{P}\cdot\mathbf{T_{cm}}\begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix} = \mathbf{C}\begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \\ C_{31} & C_{32} & C_{33} & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix}$$

$$\mathbf{P} = \begin{bmatrix} s_x f & 0 & x_0 & 0 \\ 0 & s_y f & y_0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \mathbf{T_{cm}} = \begin{bmatrix} R_{11} & R_{12} & R_{13} & T_x \\ R_{21} & R_{22} & R_{23} & T_y \\ R_{31} & R_{32} & R_{33} & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Intrinsic Matrix | Extrinsic Matrix

Camera Calibration (3/6)

- The relationships between the camera screen coordinates (x_c, y_c) and the camera coordinates (X_c, Y_c, Z_c) can be represented as below:



Intrinsic Matrix

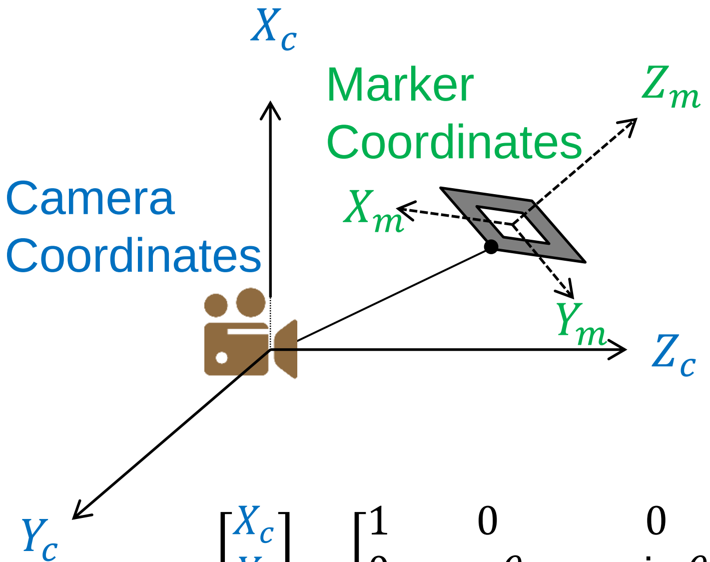
$$\begin{bmatrix} hx_c \\ hy_c \\ h \\ 1 \end{bmatrix} = \mathbf{P} \begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} = \begin{bmatrix} s_x f & 0 & x_0 & 0 \\ 0 & s_y f & y_0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix}$$

$$x_c = s_x f \frac{X_c}{Z_c} + x_0$$

$$y_c = s_y f \frac{Y_c}{Z_c} + y_0$$

Camera Calibration (4/6)

- The relationships between the camera coordinates (X_c, Y_c, Z_c) and the marker coordinates (X_m, Y_m, Z_m) can be represented as below:



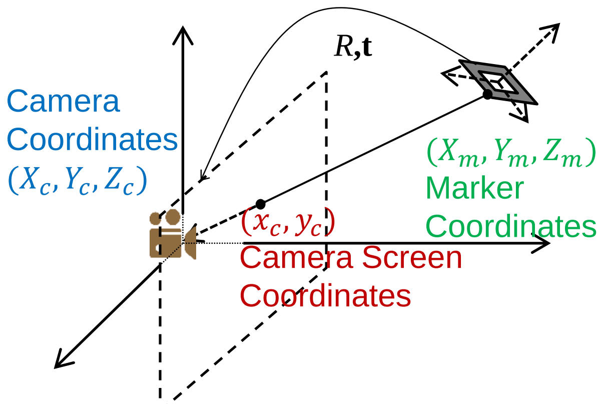
Extrinsic Matrix

$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} = \mathbf{T_{cm}} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & R_{13} & T_x \\ R_{21} & R_{22} & R_{23} & T_y \\ R_{31} & R_{32} & R_{33} & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix}$$

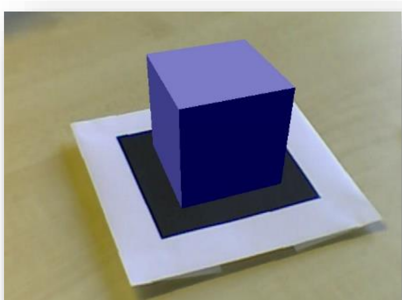
$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & -\sin\theta_x \\ 0 & \sin\theta_x & \cos\theta_x \end{bmatrix} \begin{bmatrix} \cos\theta_y & 0 & \sin\theta_y \\ 0 & 1 & 0 \\ -\sin\theta_y & 0 & \cos\theta_y \end{bmatrix} \begin{bmatrix} \cos\theta_z & -\sin\theta_z & 0 \\ \sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_m \\ Y_m \\ Z_m \end{bmatrix} + \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix}$$

Camera Calibration (5/6)

- So the relationships between the camera screen coordinates (x_c, y_c) and the marker coordinates (X_m, Y_m, Z_m) can be represented as below:



$$\begin{bmatrix} hx_c \\ hy_c \\ h \\ 1 \end{bmatrix} = \mathbf{P} \begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} = \mathbf{P} \cdot \mathbf{T_{cm}} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix} = \mathbf{C} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix} = \underbrace{\begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \\ C_{31} & C_{32} & C_{33} & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{11} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix}$$



$$\mathbf{P} = \underbrace{\begin{bmatrix} s_x f & 0 & x_0 & 0 \\ 0 & s_y f & y_0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{4}, \ \mathbf{T_{cm}} = \underbrace{\begin{bmatrix} R_{11} & R_{12} & R_{13} & T_x \\ R_{21} & R_{22} & R_{23} & T_y \\ R_{31} & R_{32} & R_{33} & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{6}$$

Camera Calibration (6/6)

- A scalar variable k is added into $\mathbf{P}$ because matrix $\mathbf{C}$ has 11 independent variables but matrices $\mathbf{P}$ and $\mathbf{T_{cm}}$ have 4 and 6 respectively.
- Since many pairs of (x_c, y_c) and (X_m, Y_m, Z_m) have been obtained by the procedure mentioned above, matrix $\mathbf{C}$ can be estimated.

$$\begin{bmatrix} hx_c \\ hy_c \\ h \\ 1 \end{bmatrix} = \mathbf{P} \begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} = \mathbf{P} \cdot \mathbf{T_{cm}} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix} = \mathbf{C} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix} = \underbrace{\begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \\ C_{31} & C_{32} & C_{33} & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{11} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix}$$

$$\mathbf{P} = \underbrace{\begin{bmatrix} s_x f & k & x_0 & 0 \\ 0 & s_y f & y_0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{5}, \mathbf{T_{cm}} = \underbrace{\begin{bmatrix} R_{11} & R_{12} & R_{13} & T_x \\ R_{21} & R_{22} & R_{23} & T_y \\ R_{31} & R_{32} & R_{33} & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{6}$$

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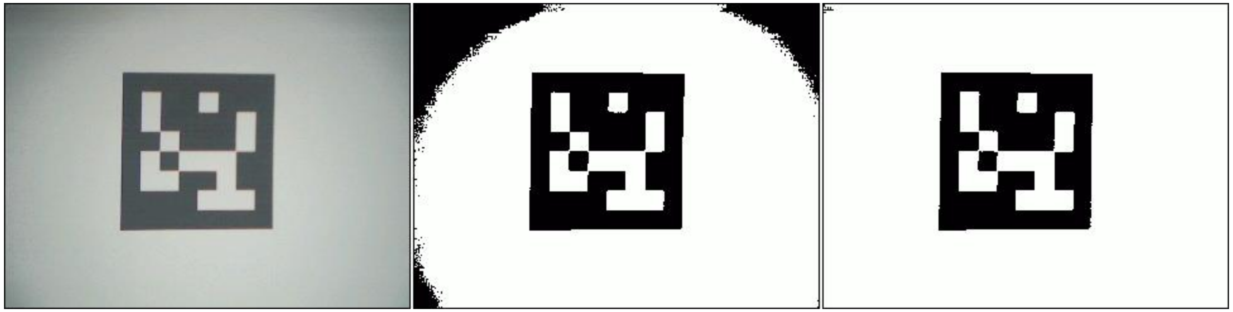
Marker Tracking

- The tracking pipeline consists of four basic steps[2]:
  1) Thresholding
  2) Fiducial Marker detection
  3) Rectangle fitting
  4) Pattern checking

[2] Schmalstieg, Dieter, and Daniel Wagner. "Experiences with handheld augmented reality." ISMAR 2007.

Thresholding

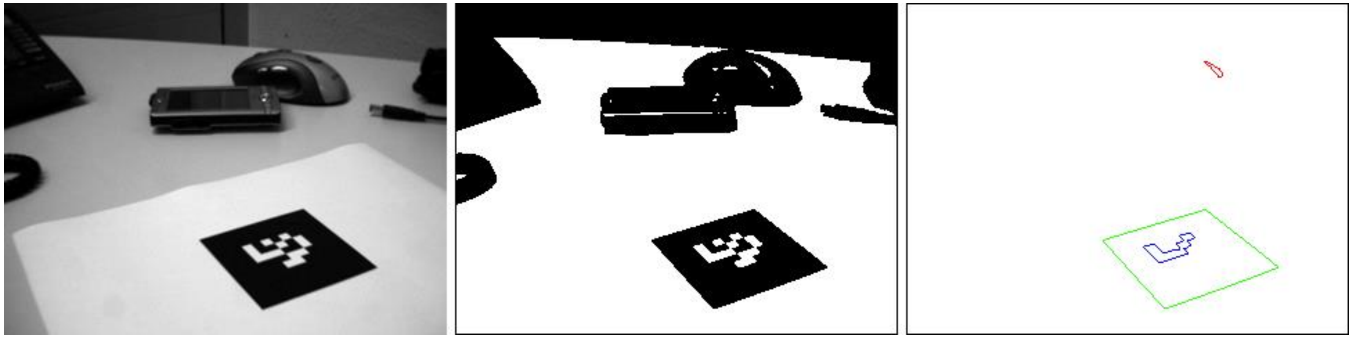
- The first step in the image processing pipeline is to convert the input image into a binary image to reliably detect the black and white portions of the fiducial markers.
- A heuristic that has proven effective is to use the median of all marker pixels extracted in the last frame as a threshold for current image.
- Vignetting compensation incorporates the radial brightness into the per-pixel threshold value.



- Vignetting. Left: original camera image. Middle: constant thresholding. Right: thresholding with vignetting compensation.

Fiducial Marker Detection

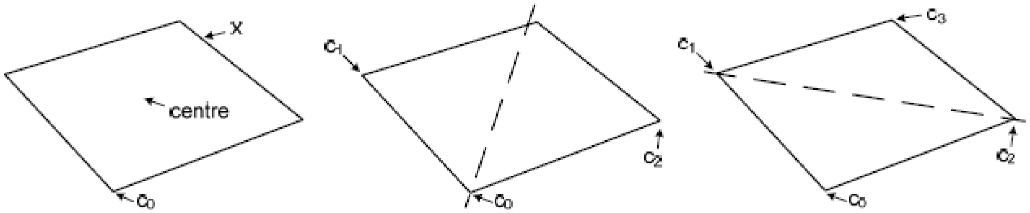
- As a first step all scan-lines are searched left to right for edges. A sequence of white followed by black pixels is considered a candidate for a marker’s border.
- The software then follows this edge until either a loop back to the start pixel is closed or until the border of the image is reached.
- All pixels that have been visited are marked as processed in order to prevent following edges more than once.



- Left: Source image; Middle: Threshold image;
  Right: Three closed polygons as candidates for rectangle fitting.

Rectangle Fitting

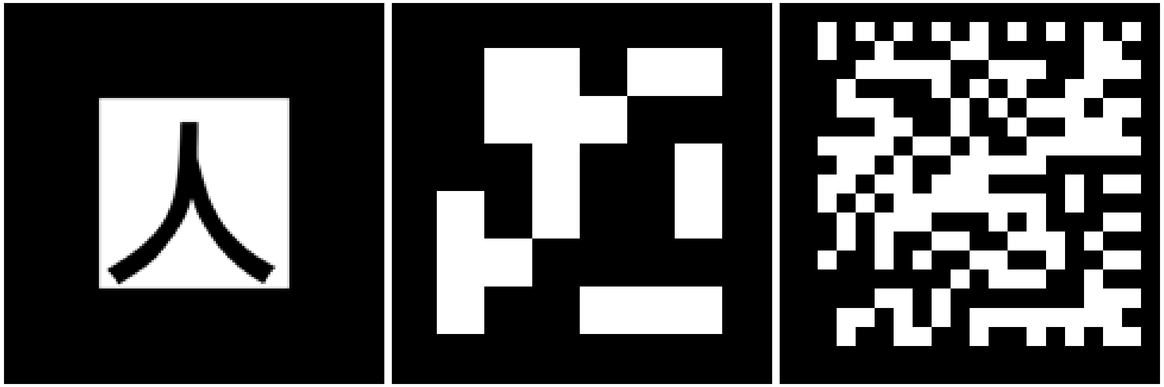
- A first corner point c_0 is selected as the contour point that lies at the maximum distance to an arbitrary starting point x of the contour.
- The center of the rectangle is estimated as the center of mass of all contour points. A line is formed from the first corner point and the center.
- Further corner points c_1, c_2 are found on each side of the line by searching for those points that have the largest distance to this line. These three corners c_0, c_1, c_2 are used to construct more lines and recursively search for additional corners.
- An iterative process searches for corners until the whole contour has been searched or more than four corner points are detected.



- Example for fitting a rectangle to a polygon

Pattern Checking

- First a marker's interior region is resampled into a normalized arrays of pixels.
- For perspectively correct unprojection, the homography matrix is computed from the markers' corner points, which are assumed to form a rectangle.
- ARToolKit uses simple L2-norm template matching.
- There are several types of markers, and some are designed for efficiency.



- Marker types. Left: Template markers; Middle: BCHmarkers; Right: DataMatrix markers

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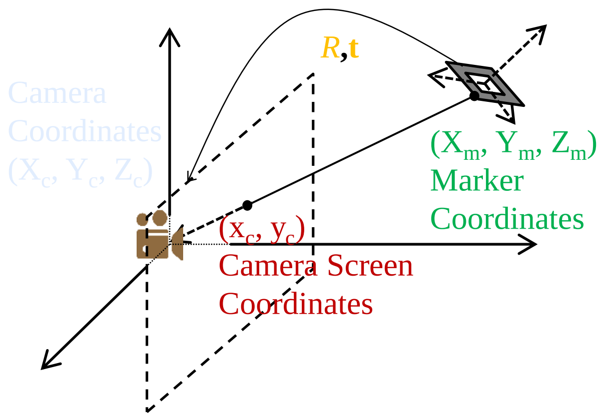
Introduction to PnP Problem

- The aim of the Perspective-n-Point (PnP) problem is to determine the position and orientation of a camera given its:
  1) intrinsic parameters
  2) a set of n correspondences between 3D points and their 2D projections.



$$\begin{bmatrix} hx_c \\ hy_c \\ h \\ 1 \end{bmatrix} = \begin{bmatrix} s_x f & 0 & x_0 & 0 \\ 0 & s_y f & y_0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \underbrace{\boxed{\begin{bmatrix} R_{11} & R_{12} & R_{13} & T_x \\ R_{21} & R_{22} & R_{23} & T_y \\ R_{31} & R_{32} & R_{33} & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix}}}_{\text{Pose}} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix}$$

Papers for Solving PnP Problem

- "Fast and Globally Convergent Pose Estimation from Video Images," TPAMI 2000. OI
- "Complete Solution Classification for the Perspective-Three-Point Problem," TPAMI 2003.
- "Linear Pose Estimation from Points or Lines," TPAMI 2003.
- "Robust Pose Estimation from a Planar Target," TPAMI 2006. RPP
- "Global Optimization through Searching Rotation Space and Optimal Estimation of the Essential Matrix," 2007 ICCV.
- "Globally Optimal O (n) Solution to the PnP Problem for General Camera Models," BMVC 2008.
- "EPnP An Accurate O(n) Solution to the PnP Problem," IJCV 2009. EPnP
- "Efficient lookup table based camera pose estimation for augmented reality, CAVW 2011.
- "A direct least-squares (DLS) method for PnP," ICCV 2011.
- "A Robust O(n) Solution to the Perspective-n-Point Problem," TPAMI 2012. RPnP
- "Revisiting the PnP Problem: A Fast, General and Optimal Solution," ICCV 2013. OPnP

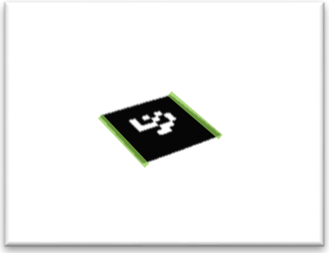
Position Estimation of Markers (1/5)

- All variables in the transformation matrix are determined by substituting screen coordinates and marker coordinates of detected marker's four vertices for (x_c, y_c) and (X_m, Y_m) respectively[3].

$$\begin{bmatrix} hx_c \\ hy_c \\ h \end{bmatrix} = \underbrace{\begin{bmatrix} N_{11} & N_{12} & N_{13} \\ N_{21} & N_{22} & N_{23} \\ N_{31} & N_{32} & 1 \end{bmatrix}}_{\text{Perspective Transformation Matrix}} \begin{bmatrix} X_m \\ Y_m \\ 1 \end{bmatrix}$$

- When two parallel sides of a square marker are projected on the image, the equations of those line segments in the camera screen coordinates are the following

$$a_1 x_c + b_1 y_c + c_1 = 0$$
$$a_2 x_c + b_2 y_c + c_2 = 0$$



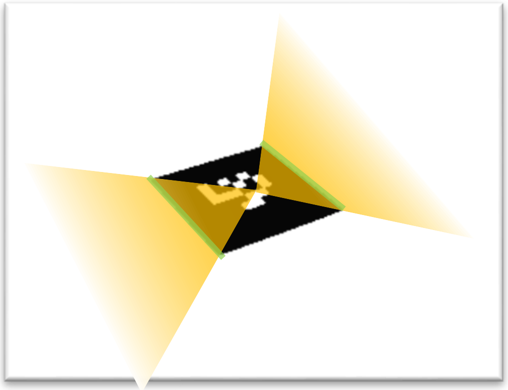
[3] Kato, Hirokazu, and Mark Billinghurst. "Marker tracking and hmd calibration for a video-based augmented reality conferencing system," IWAR 1999.

Position Estimation of Markers (2/5)

- Given the intrinsic matrix **P** that is obtained by the camera calibration, equations of the planes that include these two sides respectively can be represented in the camera coordinates.

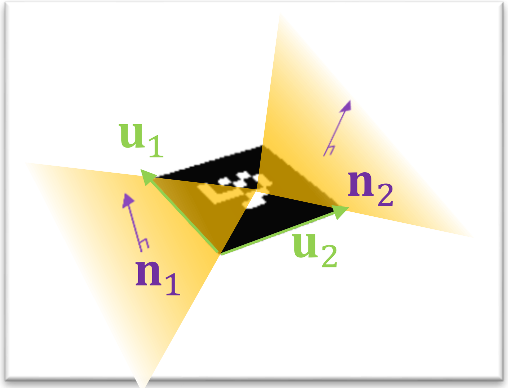
$$\begin{bmatrix} hx_c \\ hy_c \\ h \\ 1 \end{bmatrix} = \mathbf{P} \begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} & P_{13} & 0 \\ 0 & P_{22} & P_{23} & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix}$$

$$\begin{aligned} a_1 x_c + b_1 y_c + c_1 &= 0 \\ a_2 x_c + b_2 y_c + c_2 &= 0 \end{aligned} \quad \Rightarrow \quad \begin{aligned} a_1 P_{11} X_c + (a_1 P_{12} + b_1 P_{22}) Y_c + (a_1 P_{13} + b_1 P_{23} + c_1) Z_c &= 0 \\ a_2 P_{11} X_c + (a_2 P_{12} + b_2 P_{22}) Y_c + (a_2 P_{13} + b_2 P_{23} + c_2) Z_c &= 0 \end{aligned}$$



Position Estimation of Markers (3/5)

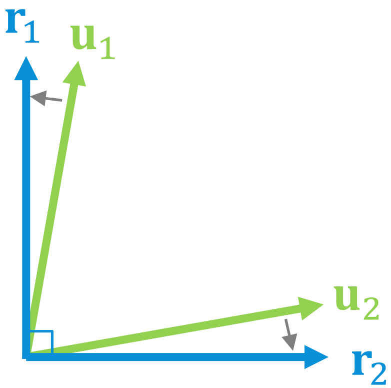
- Given that normal vectors of these planes are $\mathbf{n}_1$ and $\mathbf{n}_2$ respectively, the direction vector of parallel two sides of the square is given by the outer product $\mathbf{u}_1 = \mathbf{n}_1 \times \mathbf{n}_2$.



- Given that two unit direction vectors that are obtained from two sets of two parallel sides of the square is $\mathbf{u}_1$ and $\mathbf{u}_2$, these vectors should be perpendicular.

Position Estimation of Markers (4/5)

- However, image processing errors mean that the vectors won't be exactly perpendicular. To compensate for this two perpendicular unit, direction vectors are defined by $\mathbf{r}_1$ and $\mathbf{r}_2$ in the plane that includes $\mathbf{u}_1$ and $\mathbf{u}_2$.



$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} = \mathbf{T}_{\mathbf{cm}} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix} = \begin{array}{c} \begin{array}{cccc} \mathbf{r}_1 & \mathbf{r}_2 & \mathbf{r}_3 & \end{array} \\ \begin{bmatrix} R_{11} & R_{12} & R_{13} & T_x \\ R_{21} & R_{22} & R_{23} & T_y \\ R_{31} & R_{32} & R_{33} & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \end{array} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix}$$

- Given that the unit direction vector which is perpendicular to both $\mathbf{r}_1$ and $\mathbf{r}_2$ is $\mathbf{r}_3$, the rotation component $\mathbf{R}_{3\times3}$ in the transformation matrix $\mathbf{T}_{\mathbf{cm}}$ from marker coordinates to camera coordinates is $[\mathbf{r}_1\ \mathbf{r}_2\ \mathbf{r}_3]$.

Position Estimation of Markers (5/5)

- The four vertices coordinates of the marker in the marker coordinate frame and those coordinates in the camera screen coordinate frame, eight equations including translation component T_x T_y T_z are generated.

$$\begin{bmatrix} hx_c \\ hy_c \\ h \\ 1 \end{bmatrix} = \boxed{\begin{bmatrix} s_x f & 0 & x_0 & 0 \\ 0 & s_y f & y_0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} R_{11} & R_{12} & R_{13} & T_x \\ R_{21} & R_{22} & R_{23} & T_y \\ R_{31} & R_{32} & R_{33} & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix}} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix}$$

- The vertex coordinates of the markers in the marker coordinate frame can be transformed to coordinates in the camera screen coordinate frame by using the transformation matrix obtained.

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Conclusion

- We propose a method for tracking fiducial markers and a calibration method for camera based on the marker tracking.
  - The most important thing is to get the intrinsic and extrinsic matrix.

- The rendering part can be implemented with the transformation matrix obtained.
  - Topics of GPU group.