# 3D Machine Vision

## 3D Pose Estimation

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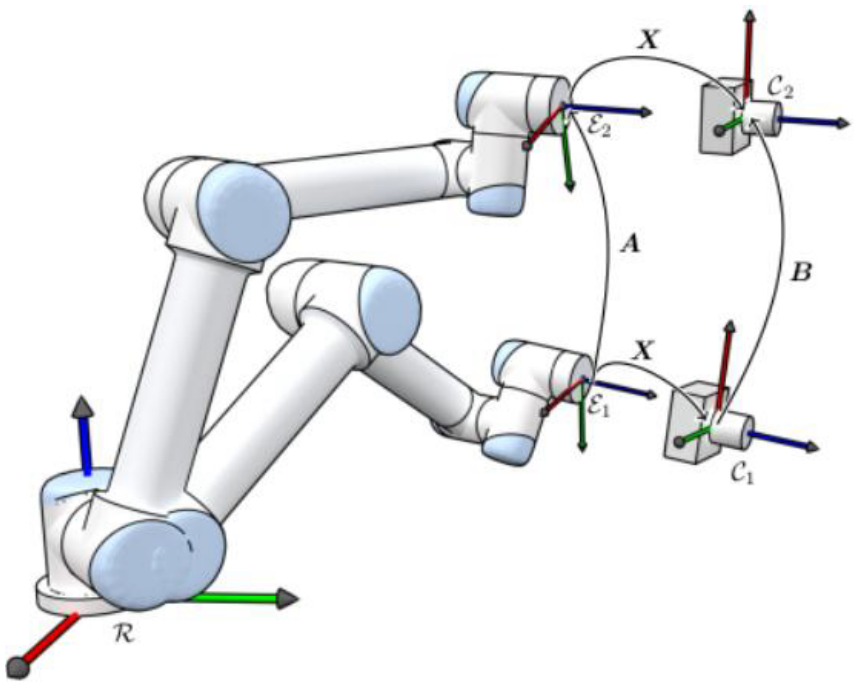
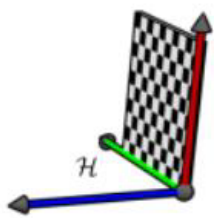
### 3D Pose Estimation

1. Hand-Eye Calibration
2. PnP Problem

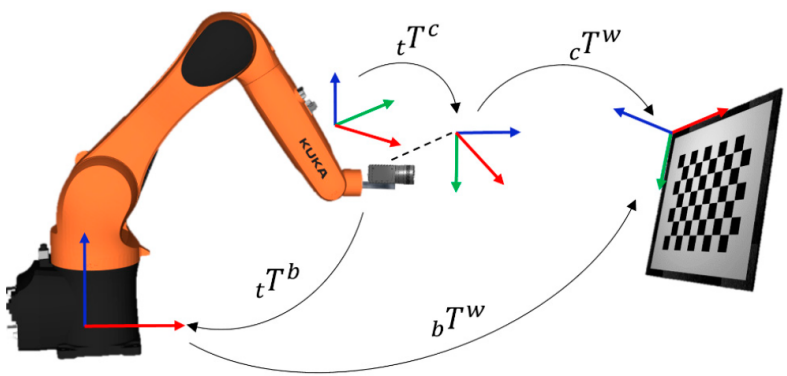


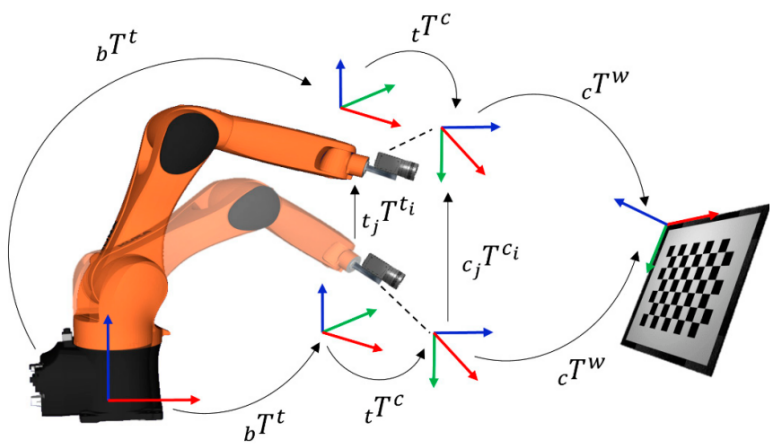
# Hand-Eye Calibration

## Problem

Hand-Eye or Eye-in-Hand Calibration is needed to measure the relative pose between the end-effector of a robot arm and a camera that is rigidly attached to the robot arm. The same principle can also be used to calibrate the relative pose between any two sensors that are rigidly attached to the same rigid body, e.g. an IMU and a camera mounted on a drone.




Robot-World-Hand-Eye




Hand-Eye

# Hand-Eye Calibration

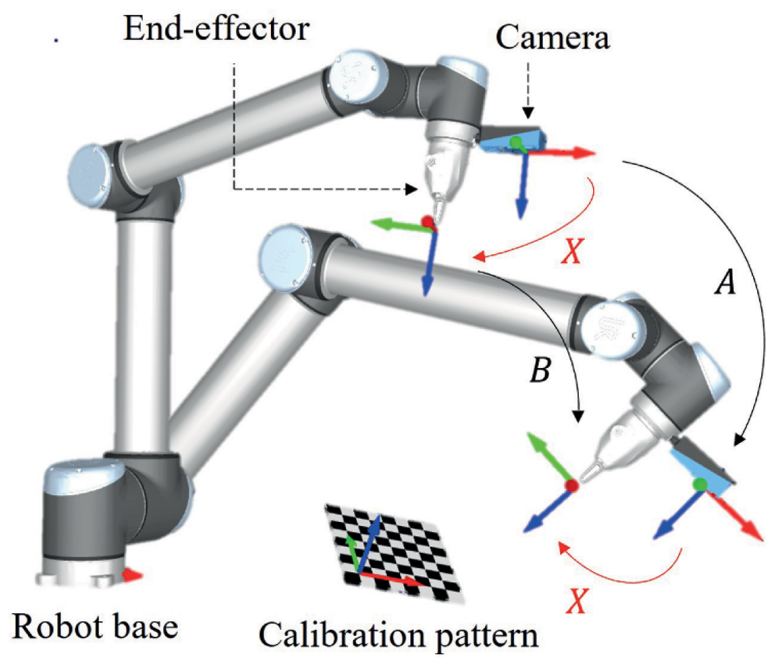
## Solution

The unknown pose between end-effector and camera is called **X**. The unknown pose between base and calibration rig is called **Y**. Depending on the (relative) poses of the end-effector $\mathbf{A}_i$ and the camera $\mathbf{B}_i$ for some number $i = 1 \ldots N$ two closed loops of pose transformations can be found:

1. $\mathbf{A}_i\mathbf{X} = \mathbf{X}\mathbf{B}_i$

2. $\mathbf{A}_i\mathbf{X} = \mathbf{Y}\mathbf{B}_i$

Once **X** is found solving for **Y** is easy.



# Hand-Eye Calibration

## Solution

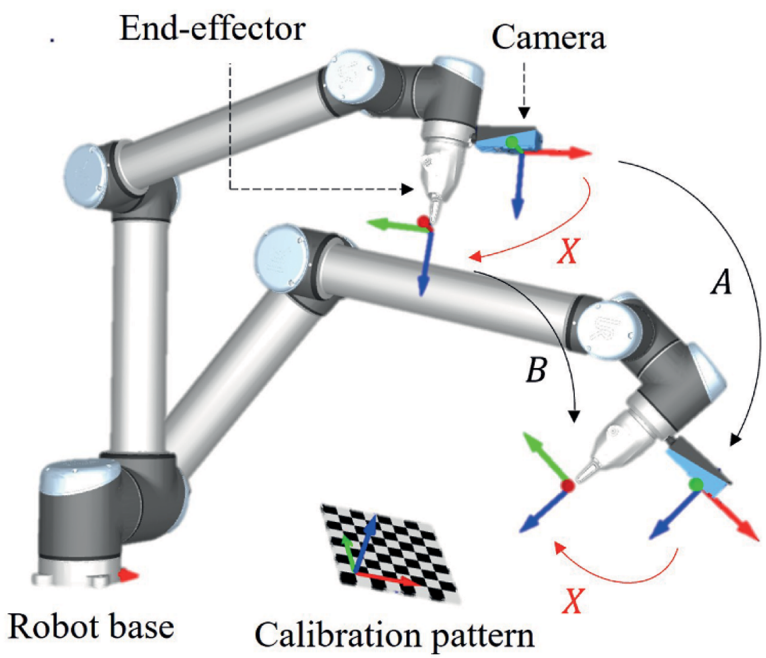
Let's solve the closed loop for rotation $\mathbf{R}_X$ and translation $\mathbf{T}_X$!

Unknown homogeneous pose transformation:

$$\mathbf{X} = \begin{bmatrix} \mathbf{R}_X & \mathbf{T}_X \\ \mathbf{0}^\top & 1 \end{bmatrix}$$

Known homogeneous pose transformations:

$$\mathbf{A}_i = \begin{bmatrix} \mathbf{R}^i_A & \mathbf{T}^i_A \\ \mathbf{0}^\top & 1 \end{bmatrix} \quad \mathbf{B}_i = \begin{bmatrix} \mathbf{R}^i_B & \mathbf{T}^i_B \\ \mathbf{0}^\top & 1 \end{bmatrix}$$



# Hand-Eye Calibration

## Solution

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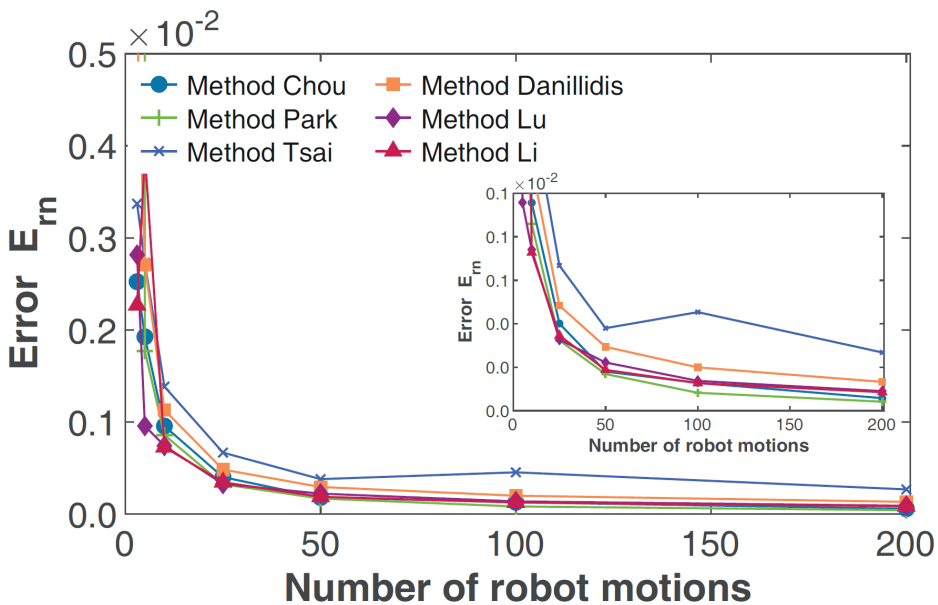
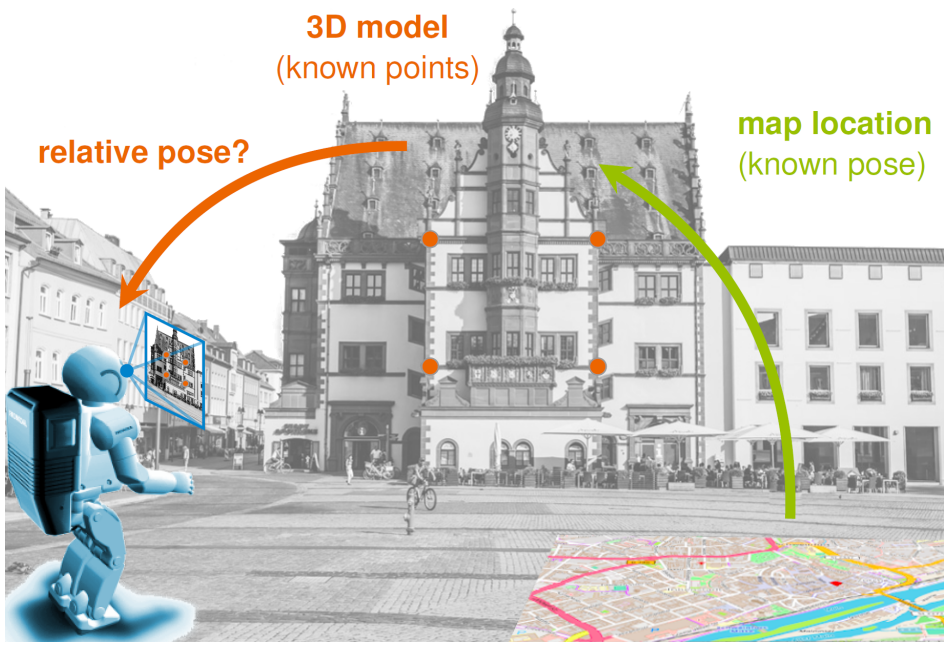
There are many different approaches how to solve for **X**. A compact and easy to understand comparison can be found in:
*Enebuse et al., Accuracy evaluation of hand-eye calibration techniques for vision-guided robots, PlosOne, 2022.*



# PnP Problem

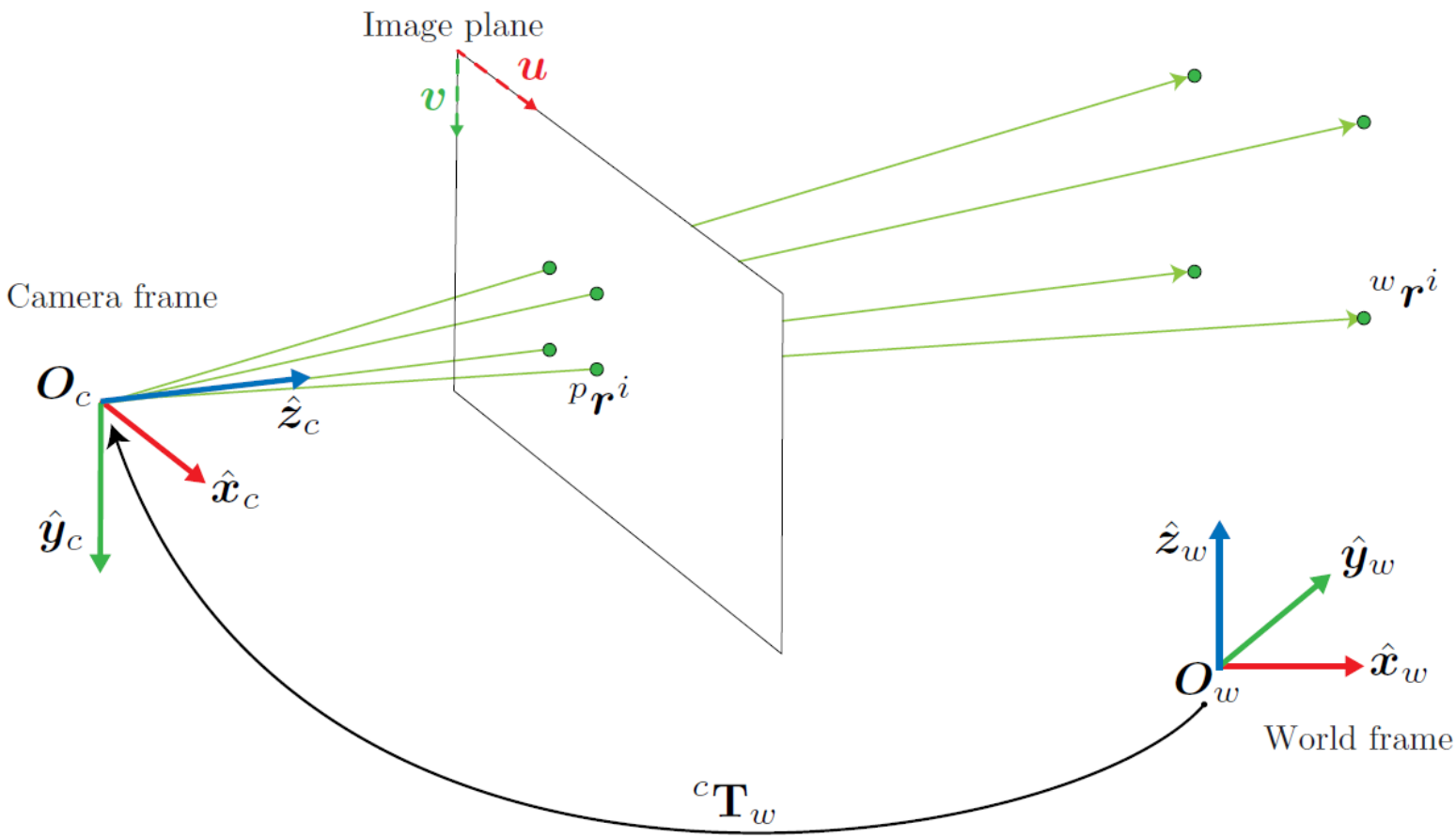
## Definition

Camera or space resection is a term used in photogrammetry in which the relative spatial position and orientation of a camera are obtained by using image measurements of some defined control points. A control point is a distinct location in 3D space with known coordinates in a given frame, e.g., in the world coordinate frame. The problem of camera resection is also known in the computer vision community as the Perspective-n-Point (PnP) problem.



# PnP Problem

## Definition



# PnP Problem

## Solution

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We have already found a linear solution for known points on a plane using a planar fiducial marker (e.g. a checker board) in the Machine Vision 1 Lecture (see corresponding slides).