2D Calibration and Metrology Techniques

Dr. David J. Michael

Director of Core Vision R & D

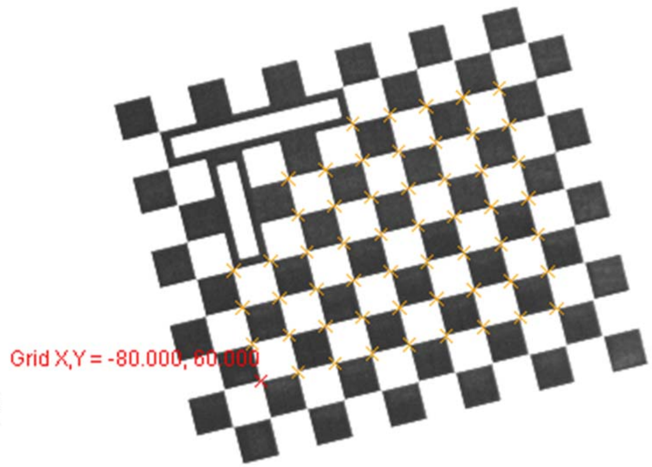
Cognex Corporation

Course Objectives

- Advanced course
- Assume that you know HOW to calibrate
  - How to **calibrate better** more frequently?
  - How to calibrate worse less often?
- Assume that you know HOW to measure
  - How can you get **better accuracy** and **more precision**?

Course Outline

- Introduction
- Calibration
  - Imaging models
  - Calibration parameters
  - Good calibration targets
  - Camera calibration for robotics



- Metrology
  - 2D or 3D measurements
  - Best accuracy/precision guidelines

Calibration - What is it?

All vision tools operate in the pixel world

What does a length of 209.41 pixels mean?

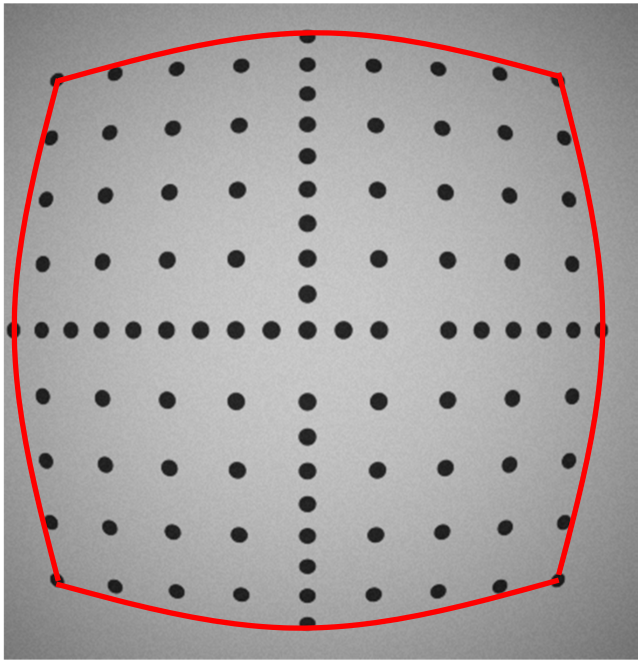
The meaning depends on the camera and environment:

1. Camera/image acquisition details
2. Physical location and angles of the camera relative to target
3. Optics (lens)

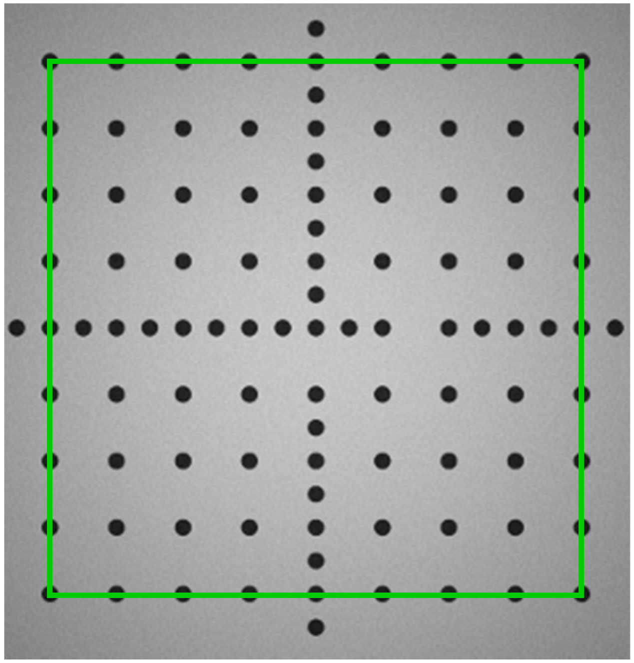
Calibrate to get real-world, meaningful measurements. This relates the world coordinate system to camera coordinate system.

Benefits of Calibration

Handles distortion



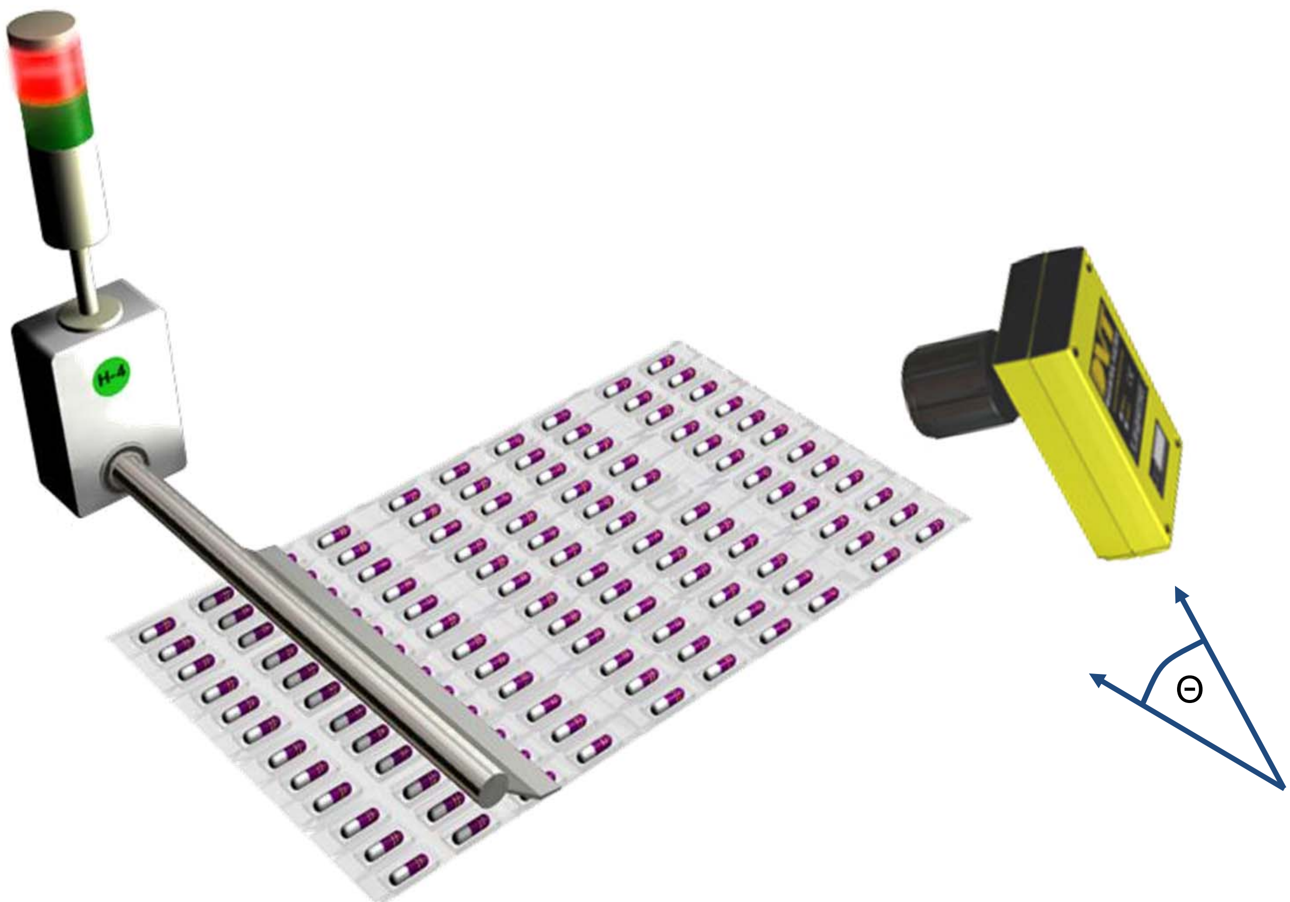
Distorted



Undistorted

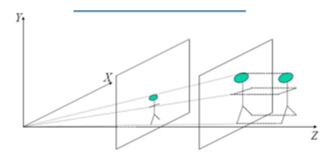
Benefits of Calibration

Handles obliquely mounted cameras



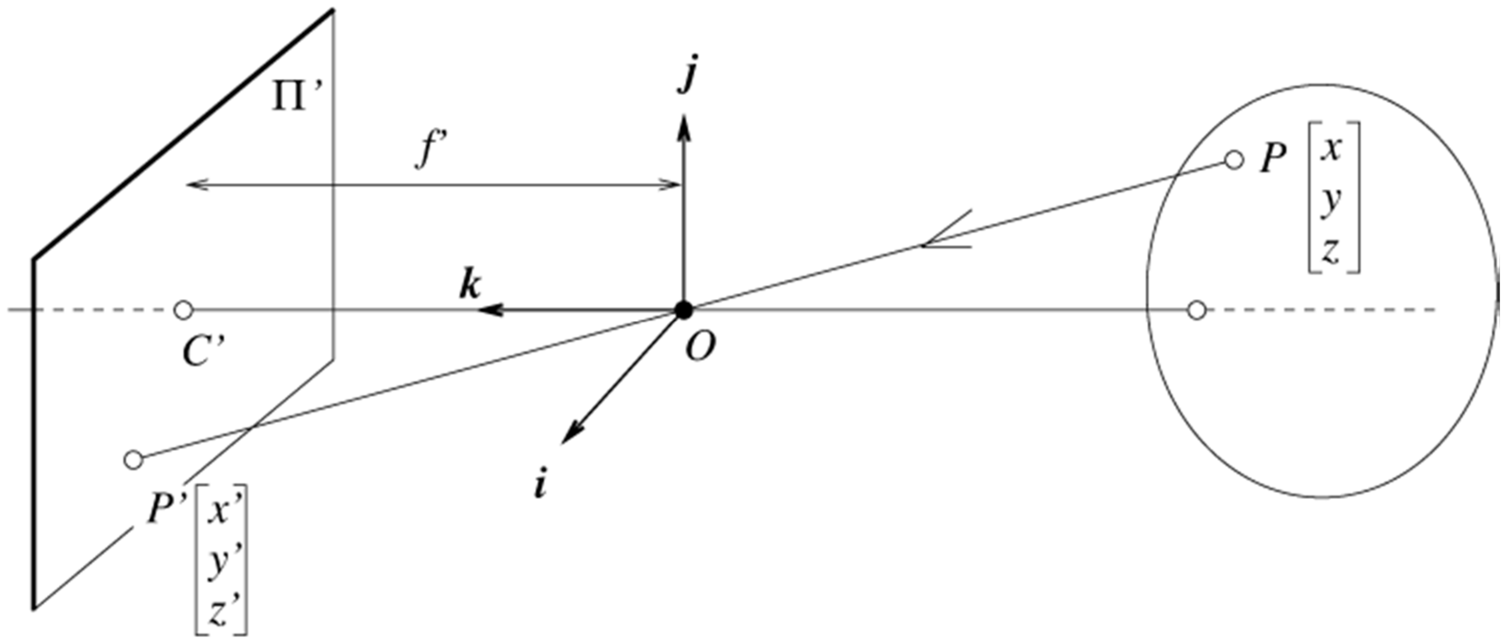
Geometric Imaging Models

- Projection (3D to 2D)
  - Orthographic projection
    - **Good for telecentric lenses**
    - **Good for long focal length lenses**
    - **Good for shallow depth objects (relative to distance to camera)**
  - Scaled orthographic projection
  - Para-perspective
  - **Perspective**
    - **Good for most machine vision situations**
  - Object-centered

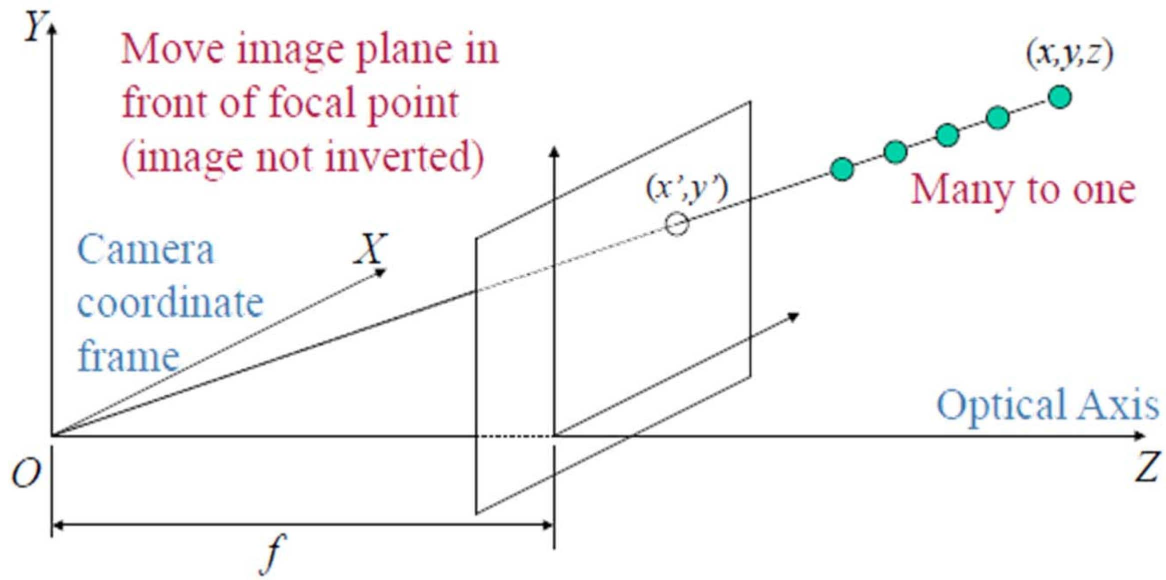


- Lens distortion
  - **Radial**
  - Tangential
  - Decentering

Perspective Imaging



Perspective Imaging



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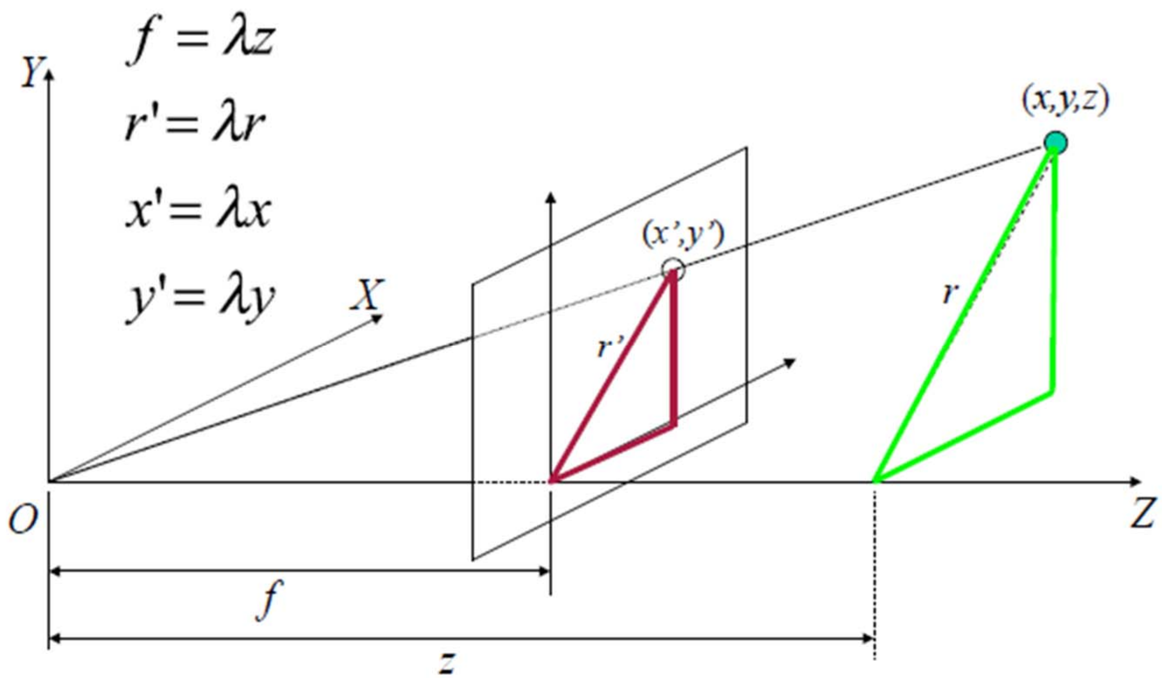

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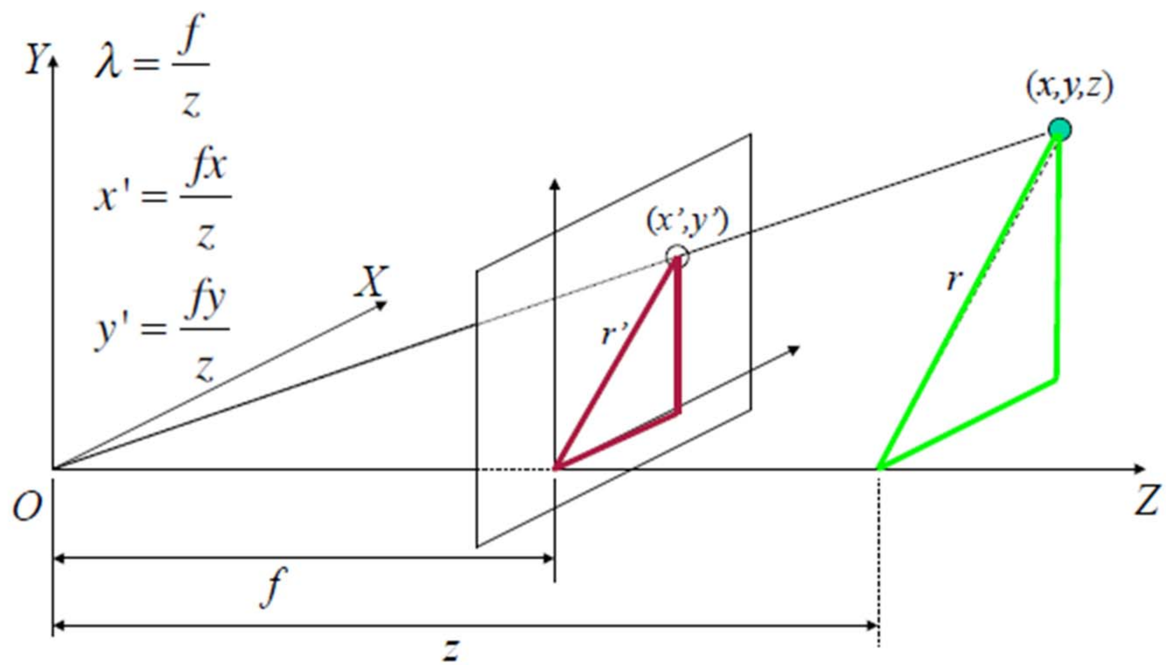


Perspective Equations

$$\underbrace{\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix}}_{(3\text{x}1)} = \underbrace{M_{\text{int}}}_{(3\text{x}3)} \underbrace{M_{ext}}_{(3\text{x}4)} \underbrace{\begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}}_{(4\text{x}1)}$$

World point

Image point $(x, y) = \begin{pmatrix} \frac{x'}{z'} \\ \frac{y'}{z'} \end{pmatrix}$

$r^2 = x^2 + y^2$

Radial lens distortion correction $\begin{pmatrix} \delta x \\ \delta y \end{pmatrix} = \begin{pmatrix} x \\ y \end{pmatrix} (k_1 r^2 + k_2 r^4 + \ldots)$

Intrinsics $M_{\text{int}} = \begin{pmatrix} fs_x & -fs_x \cot\theta & o_x \\ 0 & \frac{fs_y}{\sin\theta} & o_y \\ 0 & 0 & 1 \end{pmatrix}$

Extrinsics $M_{ext} = \begin{pmatrix} \omega_{11} & \omega_{12} & \omega_{13} & t_1 \\ \omega_{21} & \omega_{22} & \omega_{23} & t_2 \\ \omega_{31} & \omega_{32} & \omega_{33} & t_3 \end{pmatrix}$

***Calibration:** Supply many examples of World points and Image points and solve for parameters.*

Implications of Perspective

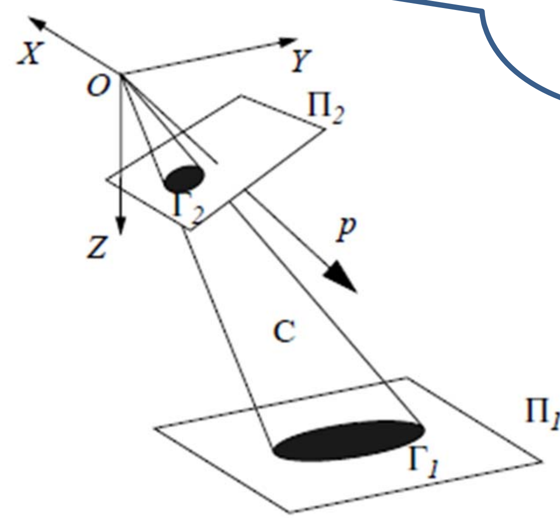
- **Preserves straight lines**
- Does not preserve parallelism
- Does not preserve angles
- Does not preserve lengths
- Does not preserve orientation
- Does not preserve circles (or center of circle)

Affine transforms preserve parallelism

Similarity transforms preserve angles

Rigid transforms preserve lengths

Translation preserves orientation



Calibration Parameters – Intrinsic Camera Parameters

- Each camera has independent intrinsics

- Focal Length (**f**)
- Principal point
  - Where the optical axis of the camera pierces the imaging array (o_x, o_y)
  - Calibrated mathematical origin in the image
- Pixel size (s_x,s_y)
- Non-orthogonality of x and y axes (skew angle **Θ**)
- Lens distortion parameters (typically **radial**)

Calibration Parameters – Intrinsic Camera Parameters

- Each camera has independent intrinsics!

- What causes intrinsics to change requiring recalibration?
  - Changing ANY lens setting including refocusing
  - Swapping the camera

Calibration Parameters – Extrinsic Camera Parameters

- Each camera has independent extrinsics!

- **Physical relationship of camera to world coordinate system**
- 6 degrees of freedom translation **t** and rotation **ω**

- What changes extrinsics to change requiring recalibration?
  - Moving or bumping the camera position
  - Swapping the camera

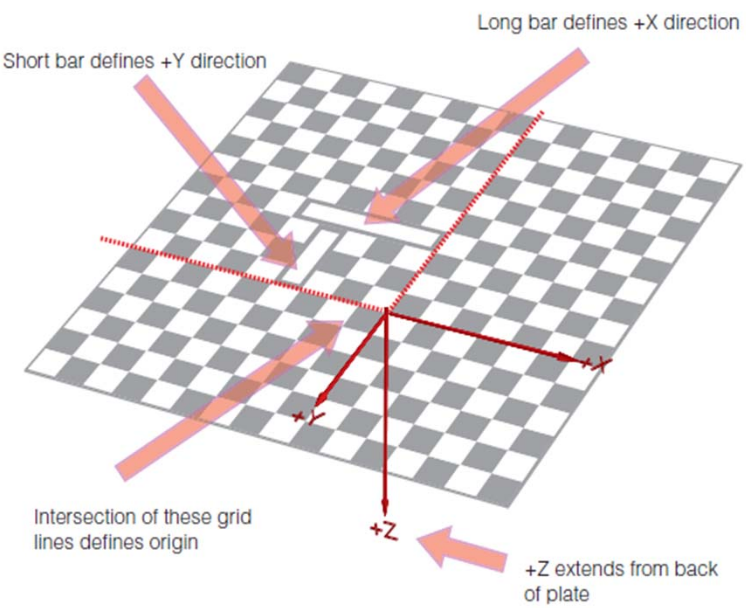
When Does Calibration Allow One-to-one Mapping?

- One-to-one mapping means that one 2D point in the image corresponds to one 3D point in the world.
  - 2D points can be used for 3D measurements with one-to-one mapping
- If objects are planar and lie on a plane or if they lie at a known depth, then this type of single camera calibration will allow 2D image measurements to imply unique 3D object measurements
- If the features are not on a plane or at a known depth, a single calibrated camera only finds 3D RAYS not 3D points
  - 3D metrology should be used with non-planar features to give high accuracy measurements

Calibration Targets

- What is the purpose of a calibration target?
  - To make it easy to calibrate
  - To make it easy to find enough (x, y, z) points to solve equations for intrinsics and extrinsics

- What makes a good calibration target?



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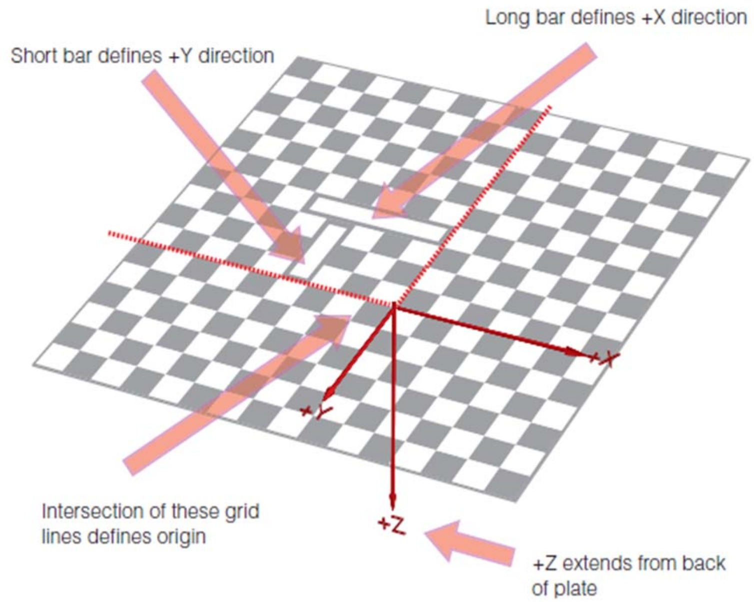
- What makes a good calibration target?
  - **Dimensionally stable and rigid**
  - **Contains highly localizable features**
  - **Is mechanically fixturable**
  - **Large enough**
  - **Matched to your vision system**
  - **Accurate**



Good Calibration Target

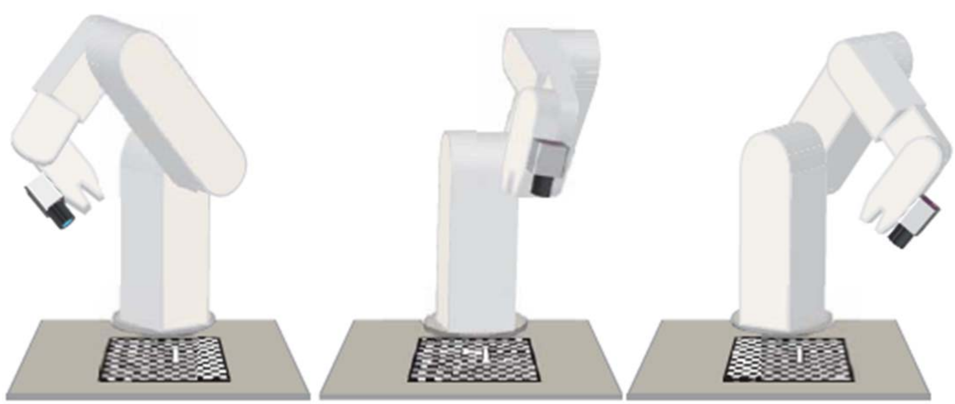
- Dimensionally stable and rigid
  - Paper target is NOT stable and rigid
- Contains highly localizable features
  - Circles (dots or holes) may be less accurate
  - Important to use a high-accuracy procedure for localization
- Is mechanically fixturable
  - Vibration or displacement will decrease accuracy
- Covers enough of the field of view to allow for accurate parameter estimation
  - Lens distortion is greater farther from the optical center
- Compatible with camera, lens, and inspection task
  - Enough features for calibration
  - Not too many features for computation time or correspondence
- Accurately manufactured target or measured after-the-fact

Why Good Calibration Accuracy is Desirable?

- Contributes to good measurement accuracy
- Detects problems in system or set-up
- Estimates what is possible for your system

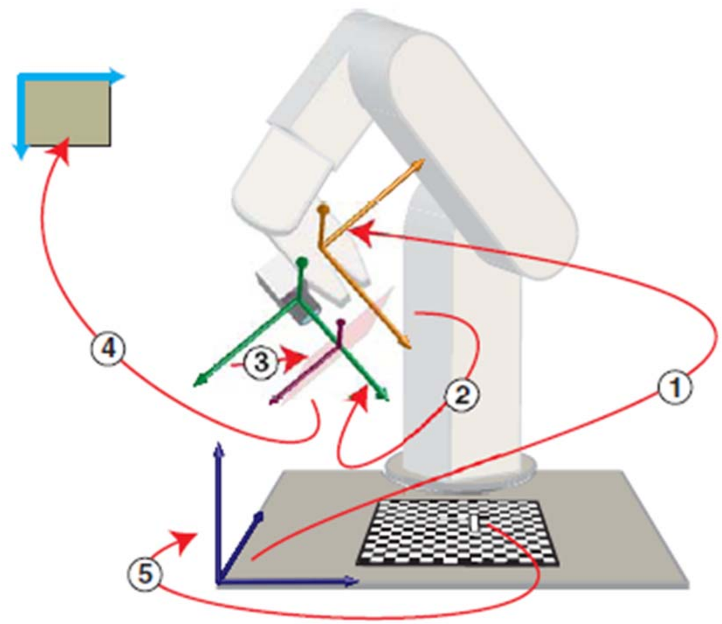
How is Robot Calibration Different?

- Need to estimate 1 more coordinate system transform (Hand-Eye Calibration)
  - From base of robot (world) to robot end-effector (hand)
  - Camera may be mounted on robot or near robot
- More likely to involve multiple cameras (or structured light sources)
- 3D effects and accuracy are typically more important



Robot Hand-Eye Calibration

Moving Camera(s)



① Hand3D space from RobotBase3D space (supplied by robot)

② Camera3D space from Hand3D space (result of hand-eye calibration)

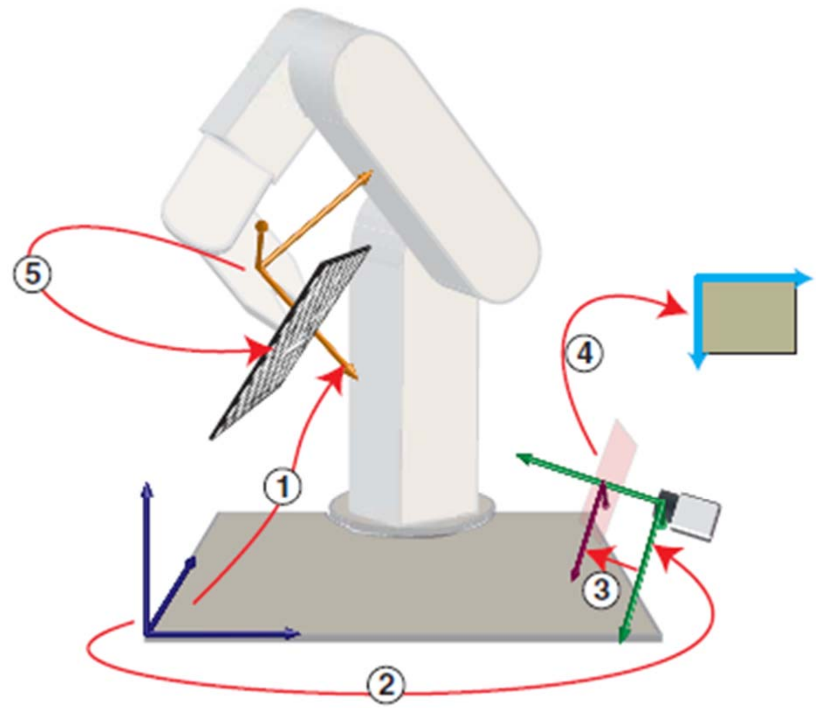
③ Camera2D space from Camera3D space (projection)

④ Raw2D space from Camera2D space (intrinsic part of original camera calibration)

⑤ RobotBase3D space from CalPlate3D space (result of hand-eye calibration)

Robot Hand-Eye Calibration

Stationary Camera(s)



1. Hand3D space from RobotBase3D space (supplied by robot)
2. RobotBase3D space from Camera3D space (result of hand-eye calibration)
3. Camera2D space from Camera3D space (projection)
4. Raw2D space from Camera2D space (intrinsic part of camera calibration)
5. CalPlate3D space from Hand3D space (result of hand-eye calibration))

Metrology

- What is typically measured using machine vision
  - Points (from templates or geometry or edge tools)
  - Lines (using line fitting or edge tools)
  - Circles (using circle fitting)

$$\text{distance} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

- Choose either 2D or 3D techniques
  - Are features planar? (Planar features can use 2D techniques)
  - Can you use orthographic projection for optics?

How Accurately Can I Gauge?

- What part are you inspecting?
  - Smooth edges are optimal; burrs/ rough edges will reduce accuracy

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  - $1/10^{th}$ pixel accuracy is attainable if the parts are flat and have well defined edges

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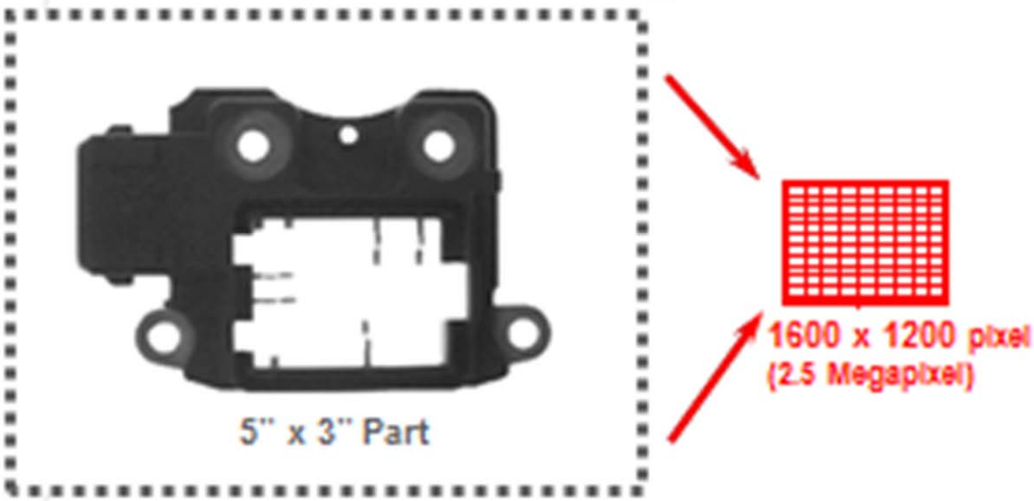
- Bottom Line: To determine the accuracy of your vision system, TEST IT!!!

How Accurately Can I Gauge?

Accuracy is a function of:

- Field of View (FOV)
- Camera Resolution (Megapixels)
- Image Quality
- Vision Tool Accuracy
- Tolerance vs. Accuracy: Factor of 10.

To estimate world coordinates accuracy, convert from pixel accuracy to world units



6.4" x 4.8" FOV

$$FOV_{horizontal} = 6.4"$$

$$Accuracy_{Vision\_Tool} = \frac{1}{10}\ pixel$$

$$\#Pixels_{horizontal} = 1600 pixels$$

$$Accuracy_{horizontal} = \frac{FOV \times Accuracy_{Vision\_Tool}}{\#Pixels}$$

$$Accuracy_{horizontal} = \frac{6.4" \times \frac{1}{10}\ pixel}{1600 pixels}$$

Accuracy $\cong$ 0.0004"

Guidelines for Metrology --- Calibration

- Keep calibration setup **identical** to production setup
  - Keep calibration object & part in same plane
  - Limit calibration to region of image containing features of interest

- Calibrate periodically – whenever you think setup may **change** (each shift, daily, etc.)

- Choose good calibration target

Guidelines for Metrology – Optics & Fixturing

- Mount the camera well
  - Rigidly
  - Vibration-free
- Choose high quality and/or telecentric lenses for best results
  - Calibrating a poor quality lens is not equivalent to using a high quality lens
- Secure the lens to the camera
  - Before calibration
- Fixture the object well

Guidelines for Metrology – Imaging and Vision Tools

- Choose features with smooth edges at selected resolution
  - Burrs/rough edges will reduce accuracy
- Select camera/illumination/exposure/gain/contrast for good image quality
  - Choose settings to minimize jitter
  - Choose settings to avoid saturation
- Choose accurate-enough vision tools for desired accuracy
  - Edge tools may have accuracy of ¼ pixel
  - PatMax may have accuracy of 1/40 pixel
- Choose 3D techniques if necessary

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Cognex Corporation
One Vision Drive
Natick, Massachusetts
USA

Phone: +1 (508) 650-3000
Email: david.michael@cognex.com

www.cognex.com