2D Calibration and Metrology Techniques

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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
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

Move image plane in front of focal point (image not inverted)

Many to one

Camera coordinate frame

Optical Axis

(x, y, z)

(x', y')

f
\[ f = \lambda z \]
\[ r' = \lambda r \]
\[ x' = \lambda x \]
\[ y' = \lambda y \]
Perspective Imaging

\[
\lambda = \frac{f}{z}
\]

\[
x' = \frac{fx}{z}
\]

\[
y' = \frac{fy}{z}
\]

\[
(x', y')
\]

\[
(x, y, z)
\]

\[
f
\]

\[
z
\]
Perspective Equations

\[
(x', y', z') = M_{\text{int}} M_{\text{ext}} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}
\]

World point

\[
(x, y, z) = \begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix}
\]

Image point

\[
r^2 = x^2 + y^2
\]

Radial lens distortion correction

\[
\begin{pmatrix} \delta x \\ \delta y \end{pmatrix} = \begin{pmatrix} x \\ y \end{pmatrix} \left( k_1 r^2 + k_2 r^4 + \ldots \right)
\]

Intrinsics

\[
M_{\text{int}} = \begin{pmatrix} f s_x & - f s_x \cot \theta & o_x \\ 0 & f s_y / \sin \theta & o_y \\ 0 & 0 & 1 \end{pmatrix}
\]

Extrinsics

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

**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)
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 \( \Theta \))

- Lens distortion parameters (typically radial)
• 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 $\omega$

• 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?
Calibration Targets

- **What is the purpose of a 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)

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

• 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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  - Vibrations can cause camera movement over time
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  – Edge tools are accurate to .25 (1/4) pixel, PatMax to .025 (1/40) pixel
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• Overall worst case is the sum of these errors.
  – These tend to be additive, and seldom cancel each other out
  – 1/10th 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:

\[
\text{Accuracy}_{\text{horizontal}} = \frac{\text{FOV}_{\text{horizontal}} \times \text{Accuracy}_{\text{Vision Tool}}}{\#\text{Pixels}_{\text{horizontal}}}
\]

\[
\text{Accuracy}_{\text{horizontal}} = \frac{6.4\text{"} \times \frac{1}{10}}{1600\text{pixels}}
\]

\[
\text{Accuracy}_{\text{horizontal}} = 0.0004\text{"}
\]
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
• 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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