Overview

• overview of positional tracking
• camera-based tracking
• HTC’s Lighthouse
• VRduino – an Arduino for VR, specifically designed for EE 267 by Keenan Molner
• pose tracking with VRduino using homographies
What are we tracking?

- Goal: track pose of headset, controller, ...

- What is a pose?
  - 3D position of the tracked object
  - 3D orientation of the tracked object, e.g. using quaternions or Euler angles

- Why? So we can map the movement of our head to the motion of the camera in a virtual environment – motion parallax!
Overview of Positional Tracking

“inside-out tracking”: camera or sensor is located on HMD, no need for other external devices to do tracking

• simultaneous localization and mapping (SLAM) – classic computer & robotic vision problem (beyond this class)

“outside-in tracking”: external sensors, cameras, or markers are required (i.e. tracking constrained to specific area)

• used by most VR headsets right now, but everyone is feverishly working on insight-out tracking!
Marker-based Tracking

- seminal papers by Rekimoto 1998 and Kato & Billinghurst 1999
- widely adopted after introduced by ARToolKit

Kato, Billinghurst - ARToolKit
Rekimoto - Matrix
Marker-based Tracking

ARToolKit

OpenCV marker tracking
Inside-out Tracking

Google’s Project Tango
also used but not shown: IMU
problem: SLAM via sensor fusion
Inside-out Tracking

• marker-less inside-out tracking used by Microsoft HoloLens, Oculus Quest, Magic Leap, ...

• eventually required by all untethered VR/AR systems

• if you need it for your own HMD, consider using Intel’s RealSense (small & has SDK)

• if you want to learn more about SLAM, take a 3D computer vision or robotic vision class, e.g. Stanford CS231A
Outside-in Tracking

- mechanical tracking
- ultra-sonic tracking
- magnetic tracking
- optical tracking
- GPS
- WIFI positioning
- marker tracking
- ...

Positional Tracking - Mechanical

some mechanical linkage, e.g.

- fakespace BOOM
- microscribe
Positional Tracking - Mechanical

pros:
- super low latency
- very accurate

cons:
- cumbersome
- “wired” by design
Positional Tracking – Ultra-sonic

- 1 transmitter, 3 receivers → triangulation
Positional Tracking – Ultra-sonic

pros:
• can be light, small, inexpensive

cons:
• line-of-sight constraints
• susceptible to acoustic interference
• low update rates
Positional Tracking - Magnetic

- reasonably good accuracy
- position and orientation
- 3 axis magnetometer in sensors
- need magnetic field generator (AC, DC, …), e.g. Helmholtz coil
- magnetic field has to oscillate and be sync’ed with magnetometers
Positional Tracking - Magnetic

pros:
• small, low cost, low latency sensors
• no line-of-sight constraints

cons:
• somewhat small working volume
• susceptible to distortions of magnetic field
• not sure how easy it is to do this untethered (need to sync)
Positional Tracking - Magnetic

Magic Leap One controller tracking:
- magnetic field generator in controller
- magnetometer in headset

https://www.ifixit.com/Teardown/Magic+Leap+One+Teardown/112245
Positional Tracking - Optical

- track active (near IR) LEDs with cameras

OR

- track passive retro-reflectors with IR illumination around camera

- both Oculus Rift and HTC Vive come with optical tracking

Oculus Rift
https://www.ifixit.com/Teardown/Oculus+Rift+C V1+Teardown/60612
Understanding Pose Estimation - Triangulation

- for tracking individual 3D points, multi-camera setups usually use triangulation

- this does not give us the pose (rotation & translation) of camera or object yet
Understanding Pose Estimation

- for pose estimation, need to track multiple points with known relative 3D coordinates!

\[
\begin{pmatrix}
  x_i \\
  y_i \\
  z_i
\end{pmatrix}
\]

\[
\begin{pmatrix}
  x_i^n \\
  y_i^n
\end{pmatrix}
\]

2D projections
Understanding Pose Estimation

- when object is closer, projection is bigger
Understanding Pose Estimation

- when object is farther, projection is smaller

... and so on ...

Estimating 6-DoF pose from 2D projections is known as the *Perspective-n-point problem*. 
Understanding Pose Estimation

1. how to get projected 2D coordinates?
2. image formation
3. estimate pose with linear homography method
4. estimate pose with nonlinear Levenberg-Marquardt method (next class)
Understanding Pose Estimation

1. how to get projected 2D coordinates?
2. image formation
3. estimate pose with linear homography method
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- HTC Lighthouse
- VRduino
HTC Lighthouse

https://www.youtube.com/watch?v=J54dotTt7k0
HTC Lighthouse

https://www.youtube.com/watch?v=J54dotTt7k0
HTC Lighthouse – Base Station

http://gizmodo.com/this-is-how-valve-s-amazing-lighthouse-tracking-technol-1705356768
HTC Lighthouse – Base Station

important specs:

• runs at 60 Hz
  • i.e. horizontal & vertical update combined 60 Hz
  • broadband sync pulses in between each laser sweep (i.e. at 120 Hz)
• each laser rotates at 60 Hz, but offset in time
• useable field of view: 120 degrees
HTC Lighthouse – Base Station

- can use up to 2 base stations simultaneously via *time-division multiplexing* (TDM)
- base station modes:
  A: TDM slave with cable sync
  B: TDM master
  C: TDM slave with optical sync
HTC Lighthouse – Base Station

- sync pulse periodically emitted (120 times per second)
- each sync pulse indicates beginning of new sweep
- length of pulse also encodes additional 3 bits of information:
- **axis**: horizontal or vertical sweep to follow
- **skip**: if 1, then laser is off for following sweep
- **data**: data bits of consecutive pulses yield OOTX frame

<table>
<thead>
<tr>
<th>Name</th>
<th>skip</th>
<th>data</th>
<th>axis</th>
<th>length (ticks)</th>
<th>length (μs)</th>
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<td>0</td>
<td>0</td>
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<td>62.5</td>
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<td>1</td>
<td>3500</td>
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<td>5000</td>
<td>104</td>
</tr>
<tr>
<td>k2</td>
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<td>0</td>
<td>1</td>
<td>5500</td>
<td>115</td>
</tr>
<tr>
<td>j3</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>6000</td>
<td>125</td>
</tr>
<tr>
<td>k3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>6500</td>
<td>135</td>
</tr>
</tbody>
</table>

https://github.com/nairol/LighthouseRedox/blob/master/docs/Light%20Emissions.md#sync-pulse
VRduino

- in this class, we use the HTC Lighthouse base stations but implement positional tracking (i.e., pose estimation) on the VRduino

- VRduino is a shield (hardware add-on) for the Arduino Teensy 3.2; custom-designed for EE 267 by Keenan Molner
VRduino
VRduino

x = -42mm, y = 25mm

x = 42mm, y = 25mm

x = -42mm, y = -25mm

x = 42mm, y = -25mm
VRduino

SCL: pin 19
SDA: pin 18
VRduino

power (3.3V)

ground
VRduino

Pin Breakout
VRduino

3.3V power, **200mA MAX**
digital R/W, Serial, cap. sense
digital R/W, Serial, cap. sense
digital R/W

digital R/W, PWM, CAN
digital R/W, PWM, CAN
digital R/W, Serial, SPI

SPI, Serial, digital R/W
digital R/W
SPI, analog read, digital R/W
SPI, analog read, digital R/W
I2C, analog read, digital R/W
I2C, analog read, digital R/W

5V power, **500mA MAX**

For more details, see Lab Writeup
Pose Estimation with the VRduino

• timing of photodiodes reported in Teensy “clock ticks” relative to last sync pulse

• Teensy usually runs at 48 MHz, so 48,000,000 clock ticks per second
How to Get the 2D Coordinates?

- at time of respective sync pulse, laser is at 90° horizontally and -90° vertically
- each laser rotates 360° in 1/60 sec
How to Get the 2D Coordinates?

- at time of respective sync pulse, laser is at 90° horizontally and -90° vertically
- each laser rotates 360° in 1/60 sec
How to Get the 2D Coordinates?

- at time of respective sync pulse, laser is at 90° horizontally and -90° vertically
- each laser rotates 360° in 1/60 sec

- convert from ticks to angle first and then to relative position on plane at unit distance

Top View

- optical axis (principle direction)
- laser sweep direction
- current laser position
- starting laser position
- laser sweep angle when it hits the photodiode

Top View
How to Get the 2D Coordinates?

raw number of ticks from photodiode

\[ \Delta t \text{[sec]} = \frac{\# \text{ticks}}{48,000,000 \left[ \frac{\text{ticks}}{\text{sec}} \right]} \]

- convert from ticks to angle first and then to relative position on plane at unit distance

Top View

\[ \Delta t \text{[sec]} = \frac{\# \text{ticks}}{48,000,000 \left[ \frac{\text{ticks}}{\text{sec}} \right]} \]

\( \alpha \)

laser sweep angle when it hits the photodiode

starting laser position 90°
How to Get the 2D Coordinates?

raw number of ticks from photodiode

\[ \Delta t [\text{sec}] = \frac{\text{# ticks}}{48,000,000 \left[ \frac{\text{ticks}}{\text{sec}} \right]} \]

\text{CPU speed}

offset from sync pulse

\[ \alpha [^\circ] = -\left( \frac{\Delta t [\text{sec}]}{1/60 \left[ \frac{\text{sec}}{^\circ} \right]} + \frac{360}{4} [^\circ] \right) \]

time per 1 revolution

- convert from ticks to angle first and then to relative position on plane at unit distance
How to Get the 2D Coordinates?

- convert from ticks to angle first and then to relative position on plane at unit distance

$$p_{i, x/y}^{2D} = \tan \left( \frac{\alpha}{360[°]} \cdot 2\pi \right)$$

Top View

offset from sync pulse

$$\alpha[°] = -\frac{\Delta t[sec]}{\frac{1}{60}[sec]} + \frac{360}{4}[°]$$

time per 1 revolution

laser sweep angle when it hits the photodiode

starting laser position $90°$
How to Get the 2D Coordinates?

**Horizontal Sweep**

\[ \alpha[^\circ] = -\frac{\Delta t[^\text{sec}]}{\frac{1}{60}[^\text{sec}] + \frac{360}{4}[^\circ]} + 360[^\circ] \]

**Vertical Sweep**

\[ \alpha[^\circ] = \frac{\Delta t[^\text{sec}]}{\frac{1}{60}[^\text{sec}] - \frac{360}{4}[^\circ]} \]
Understanding Pose Estimation

1. how to get projected 2D coordinates?
2. image formation
3. estimate pose with linear homography method
4. estimate pose with nonlinear Levenberg-Marquardt method (next class)

- how 3D points project into 2D coordinates in a camera (or a Lighthouse base station)
- very similar to graphics pipeline
Image Formation

- Image formation is a model for mapping 3D points in a local "object" coordinate system to 2D points in a "window" coordinate system.

### 3D Reference Point Arrangement

- Measured 2D projections of reference points on the device.

\[
\begin{pmatrix}
  x_i^n \\
  y_i^n
\end{pmatrix}
\]

### Planar 2D Arrangement

- Local device frame with reference points.

\[
\begin{pmatrix}
  x_i \\
  y_i \\
  z_i = 0
\end{pmatrix}
\]

- Normalized camera frame.

\[
\begin{pmatrix}
  x_i^n \\
  y_i^n
\end{pmatrix}
\]
Image Formation – 3D Arrangement

1. transform 3D point into view space:

\[
\begin{pmatrix}
    x_i^c \\
    y_i^c \\
    w_i^c
\end{pmatrix}
= \begin{pmatrix}
    1 & 0 & 0 \\
    0 & 1 & 0 \\
    0 & 0 & -1
\end{pmatrix}
\begin{pmatrix}
    r_{11} & r_{12} & r_{13} & t_x \\
    r_{21} & r_{22} & r_{23} & t_y \\
    r_{31} & r_{32} & r_{33} & t_z
\end{pmatrix}
\begin{pmatrix}
    x_i \\
    y_i \\
    z_i \\
    1
\end{pmatrix}
\]

“This is the homogeneous coordinate”

“This projection matrix”

“This modelview matrix”

3x3 rotation matrix and translation 3x1 vector

2. perspective divide:

\[
\begin{pmatrix}
    x_i^n \\
    y_i^n
\end{pmatrix}
= \begin{pmatrix}
    x_i^c / w_i^c \\
    y_i^c / w_i^c
\end{pmatrix}
\]
Image Formation – 2D Arrangement

1. transform 3D point into view space:

\[
\begin{pmatrix}
  x^c_i \\
  y^c_i \\
  w^c_i
\end{pmatrix} = \begin{pmatrix}
  1 & 0 & 0 \\
  0 & 1 & 0 \\
  0 & 0 & -1
\end{pmatrix} \begin{pmatrix}
  r_{11} & r_{12} & r_{13} & t_x \\
  r_{21} & r_{22} & r_{23} & t_y \\
  r_{31} & r_{32} & r_{33} & t_z
\end{pmatrix} \begin{pmatrix}
  x_i \\
  y_i \\
  w_i \\
  1
\end{pmatrix}
\]

= \begin{pmatrix}
  1 & 0 & 0 \\
  0 & 1 & 0 \\
  0 & 0 & -1
\end{pmatrix} \begin{pmatrix}
  r_{11} & r_{12} & t_x \\
  r_{21} & r_{22} & t_y \\
  r_{31} & r_{32} & t_z
\end{pmatrix} \begin{pmatrix}
  x_i \\
  y_i \\
  1
\end{pmatrix}

2. perspective divide:

\[
\begin{pmatrix}
  x^n_i \\
  y^n_i
\end{pmatrix} = \begin{pmatrix}
  x^c_i \\
  y^c_i \\
  w^c_i
\end{pmatrix} = \begin{pmatrix}
  x^c_i \\
  y^c_i \\
  w^c_i
\end{pmatrix} \begin{pmatrix}
  x^c_i \\
  y^c_i \\
  w^c_i
\end{pmatrix}^{-1} \begin{pmatrix}
  x_i \\
  y_i \\
  1
\end{pmatrix}
\]

\[
\begin{pmatrix}
  x^n_i \\
  y^n_i
\end{pmatrix} = \frac{1}{w^c_i} \begin{pmatrix}
  x^c_i \\
  y^c_i
\end{pmatrix} \begin{pmatrix}
  x_i \\
  y_i \\
  1
\end{pmatrix}^{-1} \begin{pmatrix}
  x^c_i \\
  y^c_i \\
  w^c_i
\end{pmatrix}^{-1} \begin{pmatrix}
  x_i \\
  y_i \\
  1
\end{pmatrix}
\]

\[
\begin{pmatrix}
  x^n_i \\
  y^n_i
\end{pmatrix} = \frac{1}{w^c_i} \begin{pmatrix}
  x^c_i \\
  y^c_i \\
  w^c_i
\end{pmatrix} \begin{pmatrix}
  x_i \\
  y_i \\
  1
\end{pmatrix}^{-1} \begin{pmatrix}
  x^c_i \\
  y^c_i \\
  w^c_i
\end{pmatrix}^{-1} \begin{pmatrix}
  x_i \\
  y_i \\
  1
\end{pmatrix}
\]
Image Formation – 2D Arrangement

- all rotation matrices are orthonormal, i.e.
  \[
  \sqrt{r_{11}^2 + r_{21}^2 + r_{31}^2} = 1 \\
  \sqrt{r_{12}^2 + r_{22}^2 + r_{32}^2} = 1
  \]

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & -1
\end{pmatrix}
\cdot
\begin{pmatrix}
r_{11} & r_{12} & t_x \\
r_{21} & r_{22} & t_y \\
r_{31} & r_{32} & t_z
\end{pmatrix}
\]
The Homography Matrix

- all rotation matrices are orthonormal, i.e.

\[
\begin{align*}
\sqrt{r_{11}^2 + r_{21}^2 + r_{31}^2} &= 1 \\
\sqrt{r_{12}^2 + r_{22}^2 + r_{32}^2} &= 1
\end{align*}
\]

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & -1
\end{pmatrix}
\begin{pmatrix}
r_{11} & r_{12} & t_x \\
r_{21} & r_{22} & t_y \\
r_{31} & r_{32} & t_z
\end{pmatrix}
= \begin{pmatrix}
h_1 & h_2 & h_3 \\
h_4 & h_5 & h_6 \\
h_7 & h_8 & h_9
\end{pmatrix}
\]

let’s call this “homography matrix”
Understanding Pose Estimation

1. how to get projected 2D coordinates?
2. image formation
3. estimate pose with linear homography method
4. estimate pose with nonlinear Levenberg-Marquardt method (next class)
   - how to compute the homography matrix
   - how to get position and rotation from that matrix
The Homography Matrix

Turns out that: any homography matrix has only 8 degrees of freedom – can scale matrix by $s$ and get the same 3D-to-2D mapping

- image formation with scaled homography matrix $sH$

$$
\begin{pmatrix}
    x^n_i \\
    w^n_i \\
    y^n_i
\end{pmatrix} = \begin{pmatrix}
    x_i^c \\
    w_i^c \\
    y_i^c
\end{pmatrix} = \begin{pmatrix}
    \frac{sh_1 x_i + sh_2 y_i + sh_3}{sh_7 x_i + sh_8 y_i + sh_9} \\
    \frac{sh_4 x_i + sh_5 y_i + sh_6}{sh_7 x_i + sh_8 y_i + sh_9}
\end{pmatrix} = \begin{pmatrix}
    s\left(\frac{h_1 x_i + h_2 y_i + h_3}{h_7 x_i + h_8 y_i + h_9}\right) \\
    s\left(\frac{h_4 x_i + h_5 y_i + h_6}{h_7 x_i + h_8 y_i + h_9}\right)
\end{pmatrix}
$$
The Homography Matrix

- common approach: estimate a scaled version of the homography matrix, where $h_9 = 1$
- we will see later how we can get scale factor $s$

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & -1
\end{pmatrix}
\begin{pmatrix}
r_{11} & r_{12} & t_x \\
r_{21} & r_{22} & t_y \\
r_{31} & r_{32} & t_z
\end{pmatrix}
= s
\begin{pmatrix}
h_1 & h_2 & h_3 \\
h_4 & h_5 & h_6 \\
h_7 & h_8 & 1
\end{pmatrix}
\]

\[\text{estimate these 8 homography matrix elements!}\]
 Pose Estimation via Homography

- image formation changes to

\[
\begin{pmatrix}
  x_i^c \\
y_i^c \\
w_i^c
\end{pmatrix} = s
\begin{pmatrix}
  h_1 & h_2 & h_3 \\
h_4 & h_5 & h_6 \\
h_7 & h_8 & 1
\end{pmatrix}
\begin{pmatrix}
x_i \\
y_i \\
1
\end{pmatrix}
\]

homography matrix with 8 unknowns!
Pose Estimation via Homography

- image formation changes to

\[
\begin{pmatrix}
  x_i^c \\
  y_i^c \\
  w_i^c
\end{pmatrix} = s
\begin{pmatrix}
  h_1 & h_2 & h_3 \\
  h_4 & h_5 & h_6 \\
  h_7 & h_8 & 1
\end{pmatrix}
\begin{pmatrix}
  x_i \\
  y_i \\
  1
\end{pmatrix}
\]

\[
\begin{pmatrix}
  x_i^n \\
  y_i^n
\end{pmatrix} = \begin{pmatrix}
  x_i^c \\
  w_i^c \\
  y_i^c \\
  w_i^c
\end{pmatrix} = \begin{pmatrix}
  h_1 x_i + h_2 y_i + h_3 \\
  h_4 x_i + h_5 y_i + h_6 \\
  h_7 x_i + h_8 y_i + 1
\end{pmatrix}
\]
Pose Estimation via Homography

- multiply by denominator

\[
\begin{pmatrix}
  x_i^n \\
  y_i^n \\
  w_i^n
\end{pmatrix} = \begin{pmatrix}
  \frac{x_i^c}{w_i^c} \\
  \frac{y_i^c}{w_i^c}
\end{pmatrix} = \begin{pmatrix}
  \frac{h_1 x_i + h_2 y_i + h_3}{h_7 x_i + h_8 y_i + 1} \\
  \frac{h_4 x_i + h_5 y_i + h_6}{h_7 x_i + h_8 y_i + 1}
\end{pmatrix}
\]

\[
x_i^n (h_7 x_i + h_8 y_i + 1) = h_1 x_i + h_2 y_i + h_3
\]
\[
y_i^n (h_7 x_i + h_8 y_i + 1) = h_4 x_i + h_5 y_i + h_6
\]
Pose Estimation via Homography

- reorder equations

\[
\begin{align*}
    h_1 x_i + h_2 y_i + h_3 - h_7 x_i x_i^n - h_8 y_i x_i^n &= x_i^n \\
    h_4 x_i + h_5 y_i + h_6 - h_7 x_i y_i^n - h_8 y_i y_i^n &= y_i^n
\end{align*}
\]

\[
\begin{align*}
    x_i^n (h_7 x_i + h_8 y_i + 1) &= h_1 x_i + h_2 y_i + h_3 \\
    y_i^n (h_7 x_i + h_8 y_i + 1) &= h_4 x_i + h_5 y_i + h_6
\end{align*}
\]
Pose Estimation via Homography

- 8 unknowns (red) but only 2 measurements (blue) per 3D-to-2D point correspondence

\[
\begin{align*}
  h_1 x_i + h_2 y_i + h_3 - h_7 x_i x_i^n - h_8 y_i x_i^n &= x_i^n \\
  h_4 x_i + h_5 y_i + h_6 - h_7 x_i y_i^n - h_8 y_i y_i^n &= y_i^n
\end{align*}
\]

- need at least 4 point correspondences to get to invertible system with 8 equations & 8 unknowns!

- VRduino has 4 photodiodes → need all 4 to compute pose
Pose Estimation via Homography

- solve $Ah = b$ on Arduino using Matrix Math Library via MatrixInversion function (details in lab)

$$
\begin{bmatrix}
    x_1 & y_1 & 1 & 0 & 0 & 0 & -x_1x_1^n & -y_1x_1^n \\
    0 & 0 & 0 & x_1 & y_1 & 1 & -x_1y_1^n & -y_1y_1^n \\
    x_2 & y_2 & 1 & 0 & 0 & 0 & -x_2x_2^n & -y_2x_2^n \\
    0 & 0 & 0 & x_2 & y_2 & 1 & -x_2y_2^n & -y_2y_2^n \\
    x_3 & y_3 & 1 & 0 & 0 & 0 & -x_3x_3^n & -y_3x_3^n \\
    0 & 0 & 0 & x_3 & y_3 & 1 & -x_3y_3^n & -y_3y_3^n \\
    x_4 & y_4 & 1 & 0 & 0 & 0 & -x_4x_4^n & -y_4x_4^n \\
    0 & 0 & 0 & x_4 & y_4 & 1 & -x_4y_4^n & -y_4y_4^n \\
\end{bmatrix}
\begin{bmatrix}
    h_1 \\
    h_2 \\
    h_3 \\
    h_4 \\
    h_5 \\
    h_6 \\
    h_7 \\
    h_8 \\
\end{bmatrix}
= 
\begin{bmatrix}
    x_1^n \\
    y_1^n \\
    x_2^n \\
    y_2^n \\
    x_3^n \\
    y_3^n \\
    x_4^n \\
    y_4^n \\
\end{bmatrix}
$$
Get Position from Homography Matrix

- still need scale factor $s$ to get position!

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & -1
\end{pmatrix}
\begin{pmatrix}
r_{11} & r_{12} & t_x \\
r_{21} & r_{22} & t_y \\
r_{31} & r_{32} & t_z
\end{pmatrix}
= s
\begin{pmatrix}
h_1 & h_2 & h_3 \\
h_4 & h_5 & h_6 \\
h_7 & h_8 & 1
\end{pmatrix}
\]
Get Position from Homography Matrix

- normalize homography to have approx. unit-length columns for the rotation part, such that $\sqrt{r_{11}^2 + r_{22}^2 + r_{33}^2} \approx 1$, $\sqrt{r_{12}^2 + r_{22}^2 + r_{33}^2} \approx 1$.

$$s = \frac{2}{\sqrt{h_1^2 + h_4^2 + h_7^2 + \sqrt{h_2^2 + h_5^2 + h_8^2}}}$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \cdot \begin{pmatrix} r_{11} & r_{12} & t_x \\ r_{21} & r_{22} & t_y \\ r_{31} & r_{32} & t_z \end{pmatrix} = s \begin{pmatrix} h_1 & h_2 & h_3 \\ h_4 & h_5 & h_6 \\ h_7 & h_8 & 1 \end{pmatrix}$$
Get Position from Homography Matrix

- this gives us the position as

\[
\begin{align*}
t_x &= sh_3, \\
t_y &= sh_6, \\
t_z &= -s
\end{align*}
\]

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & -1
\end{pmatrix}
\begin{pmatrix}
r_{11} & r_{12} & t_x \\
r_{21} & r_{22} & t_y \\
r_{31} & r_{32} & t_z
\end{pmatrix}
= s
\begin{pmatrix}
h_1 & h_2 & h_3 \\
h_4 & h_5 & h_6 \\
h_7 & h_8 & 1
\end{pmatrix}
\]
Get Rotation from Homography Matrix

1. get normalized 1\textsuperscript{st} column of 3x3 rotation matrix
2. get normalized 2\textsuperscript{nd} column via orthogonalization
3. get missing 3\textsuperscript{rd} column with cross product

\[
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & -1
\end{bmatrix}
\begin{bmatrix}
r_{11} & r_{12} & t_x \\
r_{21} & r_{22} & t_y \\
r_{31} & r_{32} & t_z
\end{bmatrix}
= s
\begin{bmatrix}
h_1 & h_2 & h_3 \\
h_4 & h_5 & h_6 \\
h_7 & h_8 & 1
\end{bmatrix}
\]
Get Rotation from Homography Matrix

1. get normalized 1$^\text{st}$ column of 3x3 rotation matrix

\[
\tilde{r}_1 = \begin{pmatrix} h_1 \\ h_4 \\ -h_7 \end{pmatrix}, \quad r_1 = \frac{\tilde{r}_1}{\|\tilde{r}_1\|_2}
\]

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & -1
\end{pmatrix} \cdot
\begin{pmatrix}
r_{11} & r_{12} & t_x \\
r_{21} & r_{22} & t_y \\
r_{31} & r_{32} & t_z
\end{pmatrix} = s
\begin{pmatrix}
h_1 & h_2 & h_3 \\
h_4 & h_5 & h_6 \\
h_7 & h_8 & 1
\end{pmatrix}
\]
Get Rotation from Homography Matrix

2. get normalized 2\textsuperscript{nd} column via orthogonalization

\[
\tilde{r}_2 = \begin{pmatrix}
  h_2 \\
  h_5 \\
  h_8
\end{pmatrix} - r_1 \cdot \begin{pmatrix}
  h_2 \\
  h_5 \\
  h_8
\end{pmatrix} r_1, \quad r_2 = \frac{\tilde{r}_2}{\|\tilde{r}_2\|}
\]

\[
\begin{pmatrix}
  1 & 0 & 0 \\
  0 & 1 & 0 \\
  0 & 0 & -1
\end{pmatrix} \begin{pmatrix}
  r_{11} & r_{12} & t_x \\
  r_{21} & r_{22} & t_y \\
  r_{31} & r_{32} & t_z
\end{pmatrix} = s \begin{pmatrix}
  h_1 & h_2 & h_3 \\
  h_4 & h_5 & h_6 \\
  h_7 & h_8 & 1
\end{pmatrix}
\]
Get Rotation from Homography Matrix

3. get missing 3\textsuperscript{rd} column with cross product: \( r_3 = r_1 \times r_2 \)

- \( r_3 \) this is guaranteed to be orthogonal to the other two columns

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & -1 \\
\end{pmatrix}
\begin{pmatrix}
r_{11} & r_{12} & t_x \\
r_{21} & r_{22} & t_y \\
r_{31} & r_{32} & t_z \\
\end{pmatrix}
= s
\begin{pmatrix}
h_1 & h_2 & h_3 \\
h_4 & h_5 & h_6 \\
h_7 & h_8 & 1 \\
\end{pmatrix}
\]
Get Rotation from Homography Matrix

- make 3x3 rotation matrix  \[ R = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix} \]
- convert to quaternion or Euler angles
Get Rotation from Homography Matrix

- remember Euler angles (with yaw-pitch-roll order):

\[
\begin{pmatrix}
  r_{11} & r_{12} & r_{13} \\
  r_{21} & r_{22} & r_{23} \\
  r_{31} & r_{32} & r_{33}
\end{pmatrix}
= \begin{pmatrix}
  \cos(\theta_z) & -\sin(\theta_z) & 0 \\
  \sin(\theta_z) & \cos(\theta_z) & 0 \\
  0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
  1 & 0 & 0 \\
  0 & \cos(\theta_x) & -\sin(\theta_x) \\
  0 & \sin(\theta_x) & \cos(\theta_x)
\end{pmatrix}
\begin{pmatrix}
  \cos(\theta_y) & 0 & \sin(\theta_y) \\
  0 & 1 & 0 \\
  -\sin(\theta_y) & 0 & \cos(\theta_y)
\end{pmatrix}
\]

\[
= \begin{pmatrix}
  \cos(\theta_y)\cos(\theta_z) - \sin(\theta_x)\sin(\theta_y)\sin(\theta_z) & -\cos(\theta_x)\sin(\theta_z) & \sin(\theta_y)\cos(\theta_z) + \sin(\theta_x)\cos(\theta_y)\sin(\theta_z) \\
  \cos(\theta_y)\sin(\theta_z) + \sin(\theta_x)\sin(\theta_y)\cos(\theta_z) & \cos(\theta_x)\cos(\theta_z) & \sin(\theta_y)\sin(\theta_z) - \sin(\theta_x)\cos(\theta_y)\cos(\theta_z) \\
  -\cos(\theta_x)\sin(\theta_y) & \sin(\theta_x) & \cos(\theta_x)\cos(\theta_y)
\end{pmatrix}
\]

- get angles from 3x3 rotation matrix:

\[
\begin{align*}
  r_{32} &= \sin(\theta_x) \\
  \frac{r_{31}}{r_{33}} &= \frac{-\cos(\theta_x)\sin(\theta_y)}{\cos(\theta_x)\cos(\theta_y)} = -\tan(\theta_y) \\
  \frac{r_{12}}{r_{22}} &= \frac{-\cos(\theta_x)\sin(\theta_z)}{\cos(\theta_x)\cos(\theta_z)} = -\tan(\theta_z)
\end{align*}
\]

\[
\Rightarrow \theta_x = \sin^{-1}(r_{32}) = \arcsin(r_{32})
\]

\[
\Rightarrow \theta_y = \tan^{-1}\left(-\frac{r_{31}}{r_{33}}\right) = \arctan2(-r_{31}, r_{33})
\]

\[
\Rightarrow \theta_z = \tan^{-1}\left(-\frac{r_{12}}{r_{22}}\right) = \arctan2(-r_{12}, r_{22})
\]
Temporal Filter to Smooth Noise

- pose estimation is **very** sensitive to noise in the measured 2D coordinates!

  → estimated position and especially rotation may be noisy

- apply a simple temporal filter with weight $\alpha$ to smooth the pose at time step $k$:

  $\left( \theta_x, \theta_y, \theta_z, t_x, t_y, t_z \right)_{filtered}^{(k)} = \alpha \left( \theta_x, \theta_y, \theta_z, t_x, t_y, t_z \right)_{filtered}^{(k-1)} + (1 - \alpha) \left( \theta_x, \theta_y, \theta_z, t_x, t_y, t_z \right)_{unfiltered}^{(k)}$

- smaller $\alpha \rightarrow$ less filtering, larger $\alpha \rightarrow$ more smoothing
Pose Estimation via Homographies – Step-by-Step

in each loop() call of the VRduino:

1. get timings from all 4 photodiodes in “ticks”

2. convert “ticks” to degrees and then to 2D coordinates on plane at unit distance (i.e. get $x_i^n, y_i^n$)

3. populate matrix $A$ using the 2D and 3D point coordinates

4. estimate homography as $h=A^{-1}b$

5. get position $t_x, t_y, t_z$ and rotation, e.g. in Euler angles from the estimated homography

6. apply temporal filter to smooth out noise
Must read: course notes on tracking!
Understanding Pose Estimation

1. how to get projected 2D coordinates?

2. image formation

3. estimate pose with linear homography method

4. estimate pose with nonlinear Levenberg-Marquardt method (next class)

- advanced topic
- all details of this are also derived in course notes