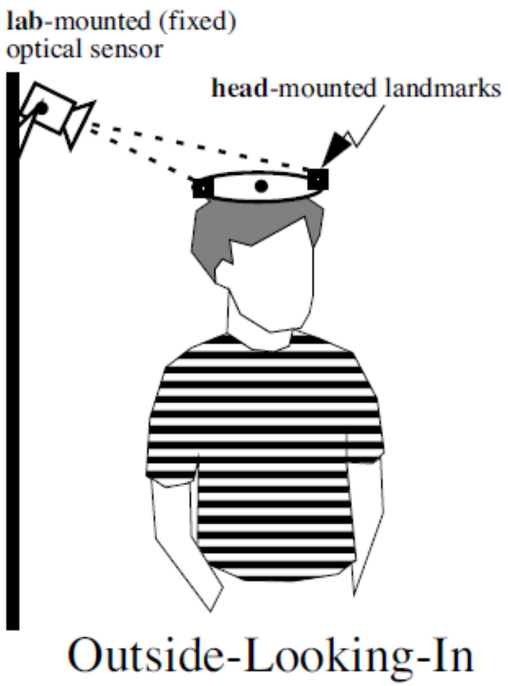
# Outside-in Tracking




Avinash Sharma
Center for Visual IT, KCIS, IIIT Hyderabad

Content is largely borrowed from Stanford Bruce Thomas (Univ. Southern Australia )and Gordon Wetzstein (Stanford Univ.)

INTERNATIONAL INSTITUTE OF INFORMATION TECHNOLOGY
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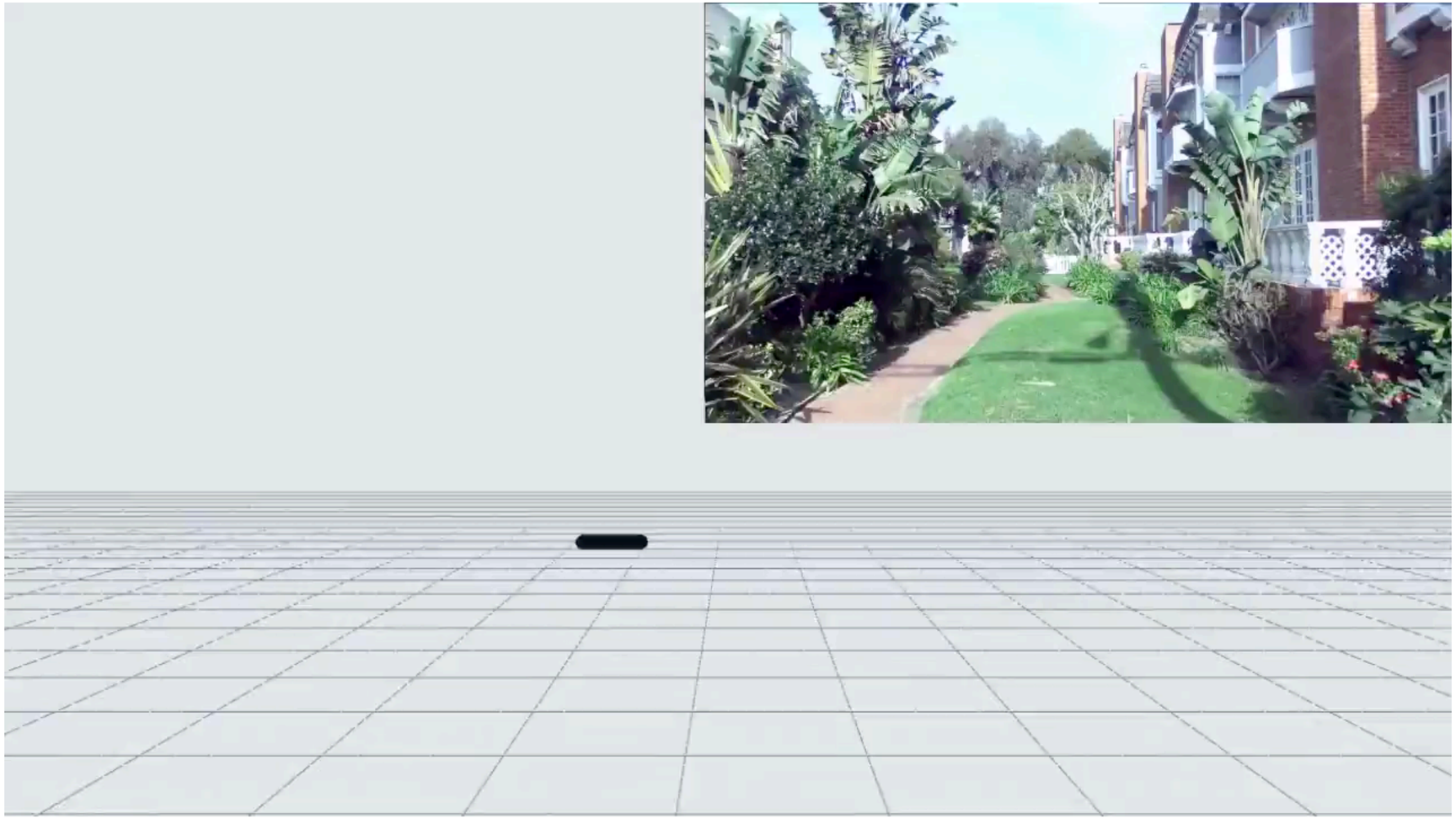
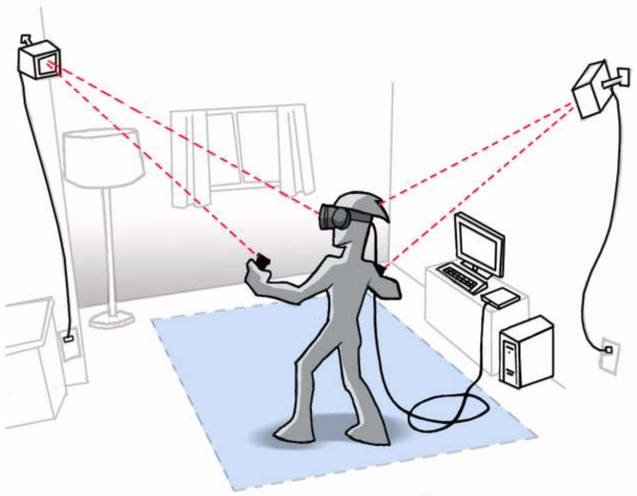
# Positional Tracking



https://www.stereolabs.com/

# Positional Tracking

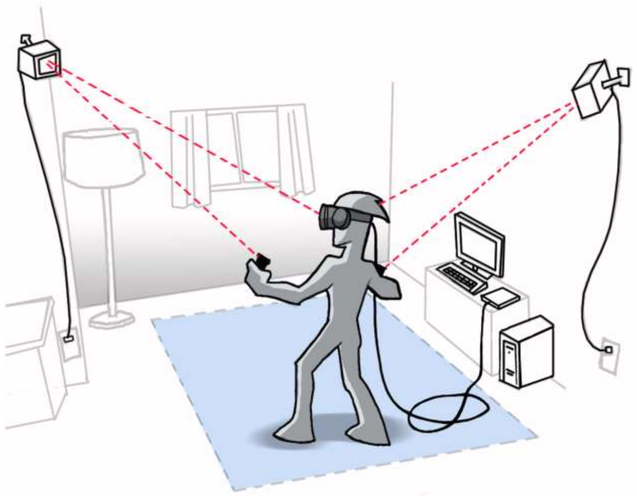
- **Outside-in Tracking**: External sensors, cameras, or markers are required.



- **Inside-out Tracking**: Camera or sensor is located on HMD, no need for other external devices to do tracking.

# Positional Tracking

- **Outside-in Tracking**: External sensors, cameras, or markers are required.



- **Inside-out Tracking**: Camera or sensor is located on HMD, no need for other external devices to do tracking.

# Outside-in Tracking

- Mechanical tracking
- Ultrasonic tracking
- Magnetic tracking
- Optical tracking
- GPS
- WIFI positioning

# Mechanical Tracking

Microscribe

Sutherland

**++: high accuracy, low jitter, low latency**
**-- : cumbersome, limited range, fixed position**

# Mechanical Tracking

BOOM (Binocular Omni-Orientation Monitor)

- Counterbalanced arm with $100^{o}$ FOV HMD mounted on it
- 6 DOF, 4mm position accuracy, 300Hz sampling, < 5 ms latency

https://www.youtube.com/watch?v=QpTQTu7A6SI

# Ultrasonic Tracking

Time of Flight or Phase-Coherence Sound Waves

Ultrasonic
Logitech

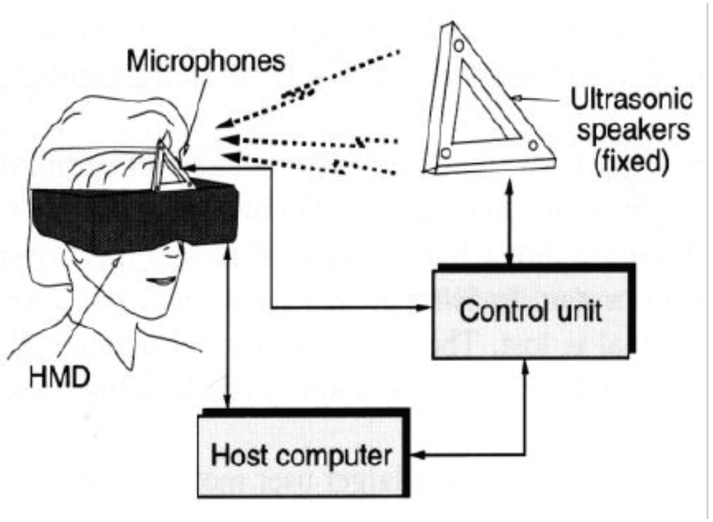
IS600

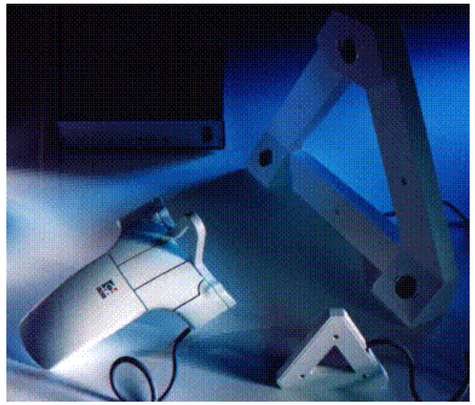
**++: Small, Cheap**

**-- : 3DOF, Line of Sight, Low resolution, Affected by Environment (pressure, temperature), Low sampling rate**

# Ultrasonic Tracking

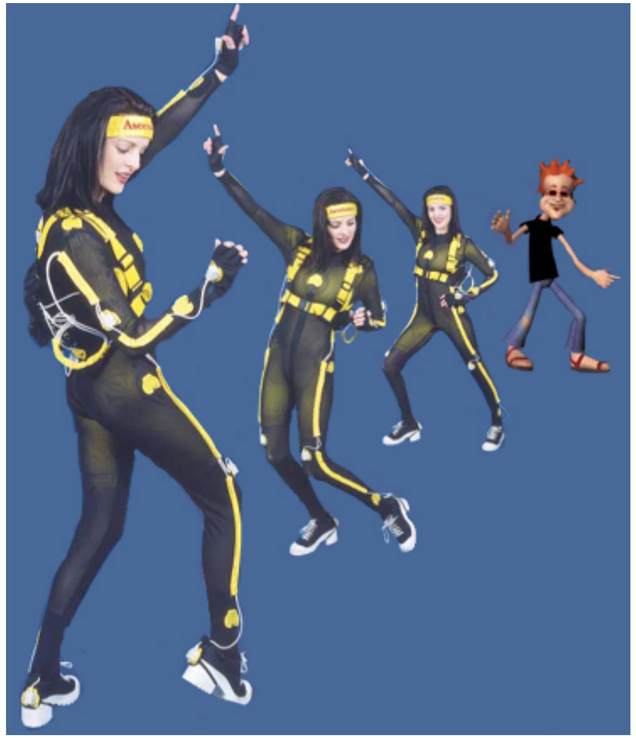
- Transmitter is a set of three ultrasonic speakers - 30cm from each other
  - Rigid and fixed triangular frame
  - 50 Hz update, 30 ms latency
- Receiver is a set of three microphones Placed at the top of the HMD
  - May be part of 3D mice, stereo glasses, or other interface devices
- Range typically about 1.5 m
  - Direct line of sight required
  - Accuracy $0.1^{o}$ orientation, 2% distance



# Magnetic Tracking

Measure difference in current between a magnetic transmitter and a receiver



**++: 6DOF, robust, accurate, no line of sight needed**

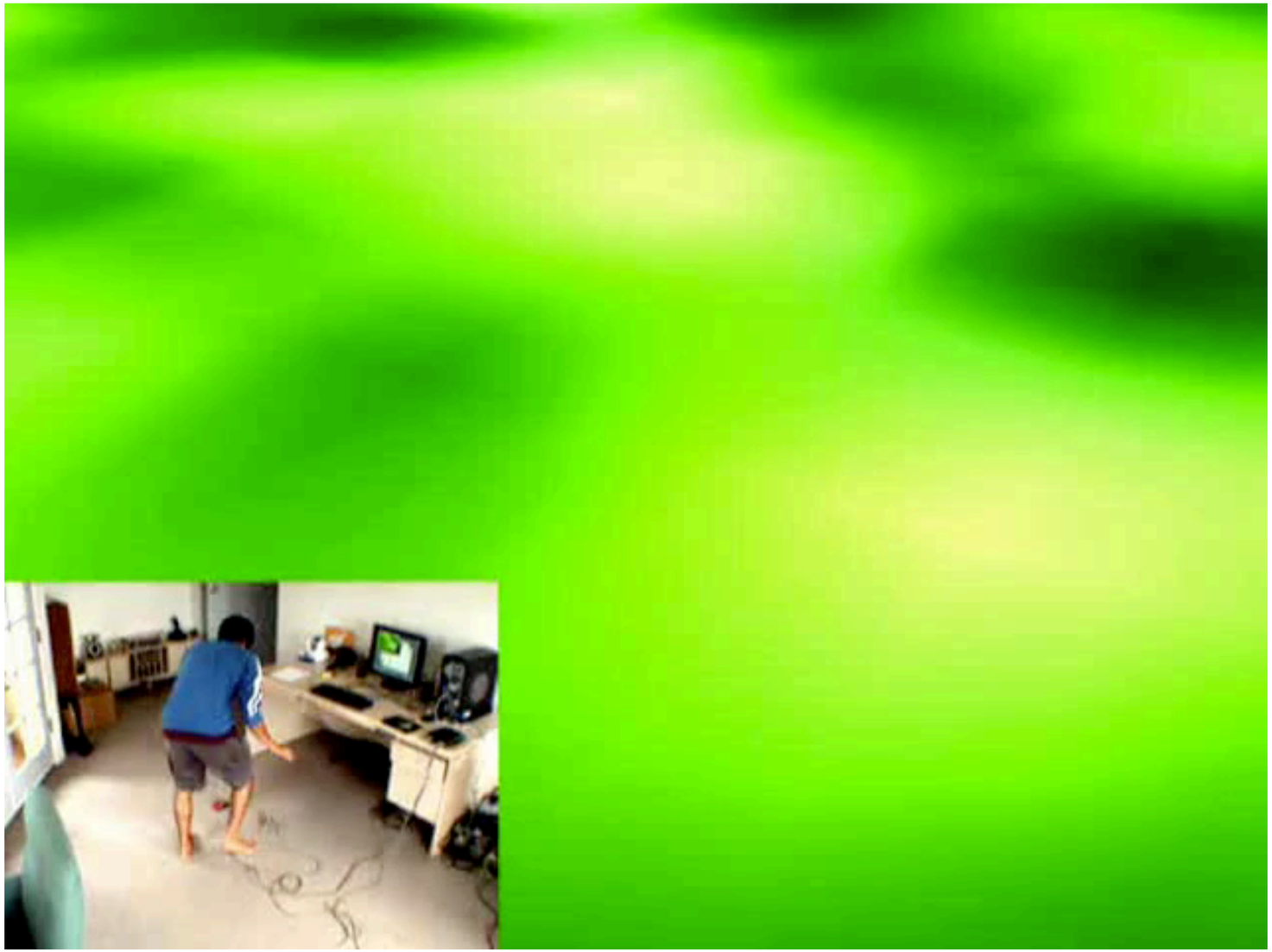
**-- : limted range, sensible to metal, noisy, expensive**

Flock of Birds (Ascension)

# Magnetic Tracking

## Polhemus Fastrak

- Degrees-of-Freedom: 6DOF
- Number of Sensors: 1-4
- Latency: 4ms
- Update Rate: 120 Hz/(num sensors)
- Static Accuracy Position: 0.03in RMS
- Static Accuracy Orientation: 0.15° RMS
- Range from Standard Source: Up to 5 feet or 1.52 meters
- Extended Range Source: Up to 15 feet or 4.6 meters



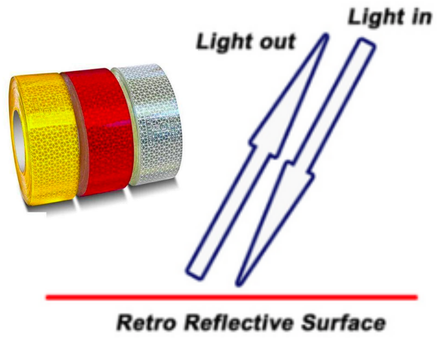
# Magnetic Tracking

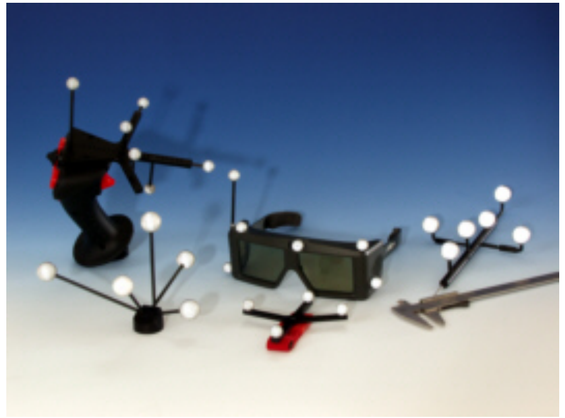
## Razer Hydra

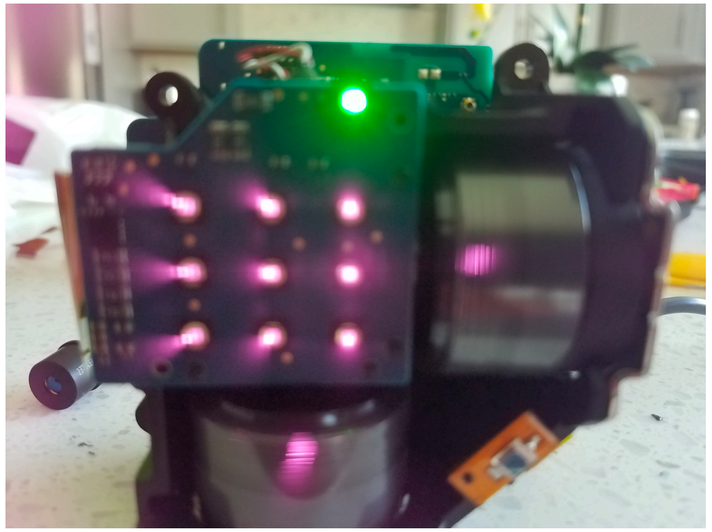
- Developed by Sixense
- Magnetic source + 2 wired controllers
  - Short range (< 1 m), Precision of 1mm and $1^{o}$
  - 62Hz sampling rate, < 50 ms latency
- $600 USD

# Optical Tracking

**Infrared (Laser), Retro-Reflective, Stereoscopic,**







**++: Long range, cheap, immune to metal**

**-- : Line of Sight, Visual Targets, Low Sampling rate**

# Optical Tracking

**Valve's SteamVR "Lighthouse" (HTC Vive)**

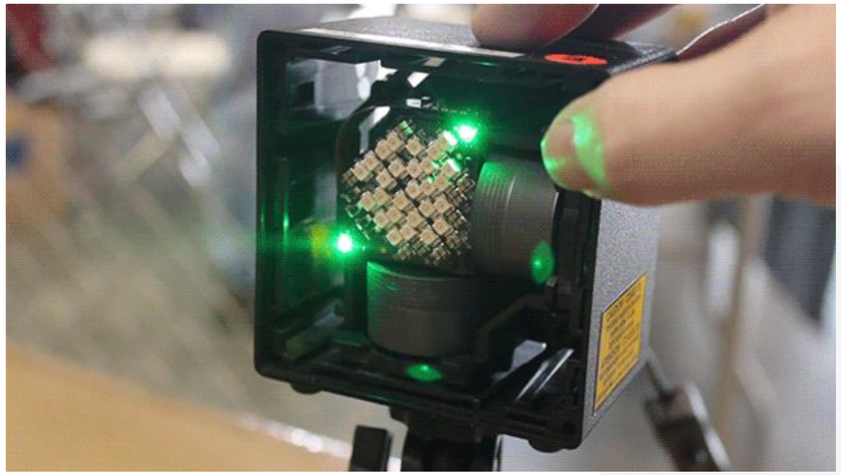
Outside-in hybrid tracking system

- Outside-in hybrid tracking system
- 2 base stations
  - Each with 2 laser scanners, LED array
- Headworn/handheld sensors
  - 37 photo-sensors in HMD, 17 in hand
  - Additional IMU sensors (500 Hz)
- Performance
  - Tracking server fuses sensor samples
  - Sampling rate 250 Hz, 4 ms latency
  - 2mm RMS tracking accuracy
  - Large area - 5 x 5m range

# Optical Tracking

**Valve's SteamVR "Lighthouse"**
**(HTC Vive)**

Outside-in hybrid tracking system



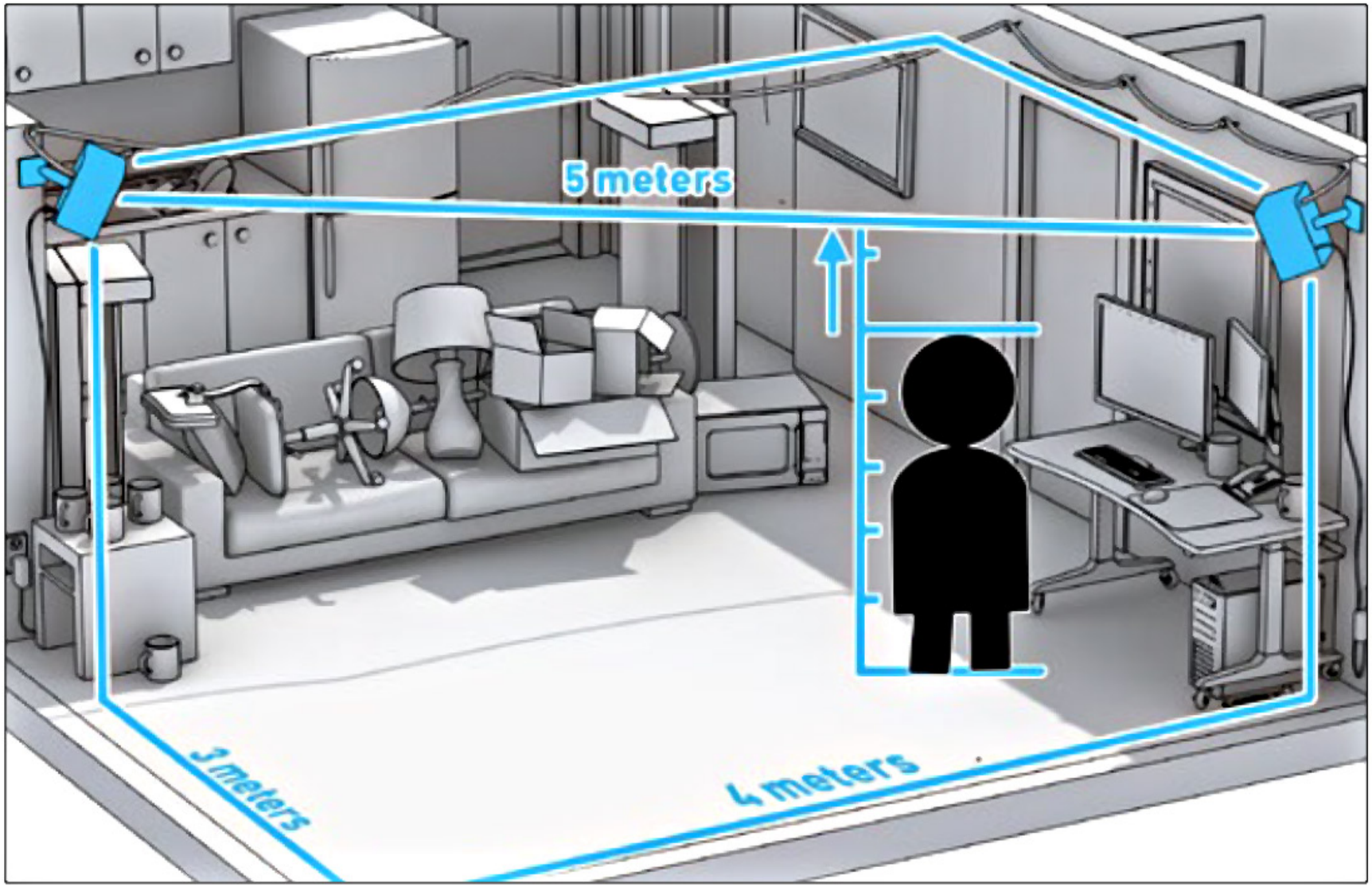
*Base station*
*- IR LED array*
*- 2 x scanned lasers*

*Head Mounted Display*
*- 37 photo sensors*
*- 9 axis IMU*

# Optical Tracking

**Valve's SteamVR "Lighthouse" (HTC Vive)**

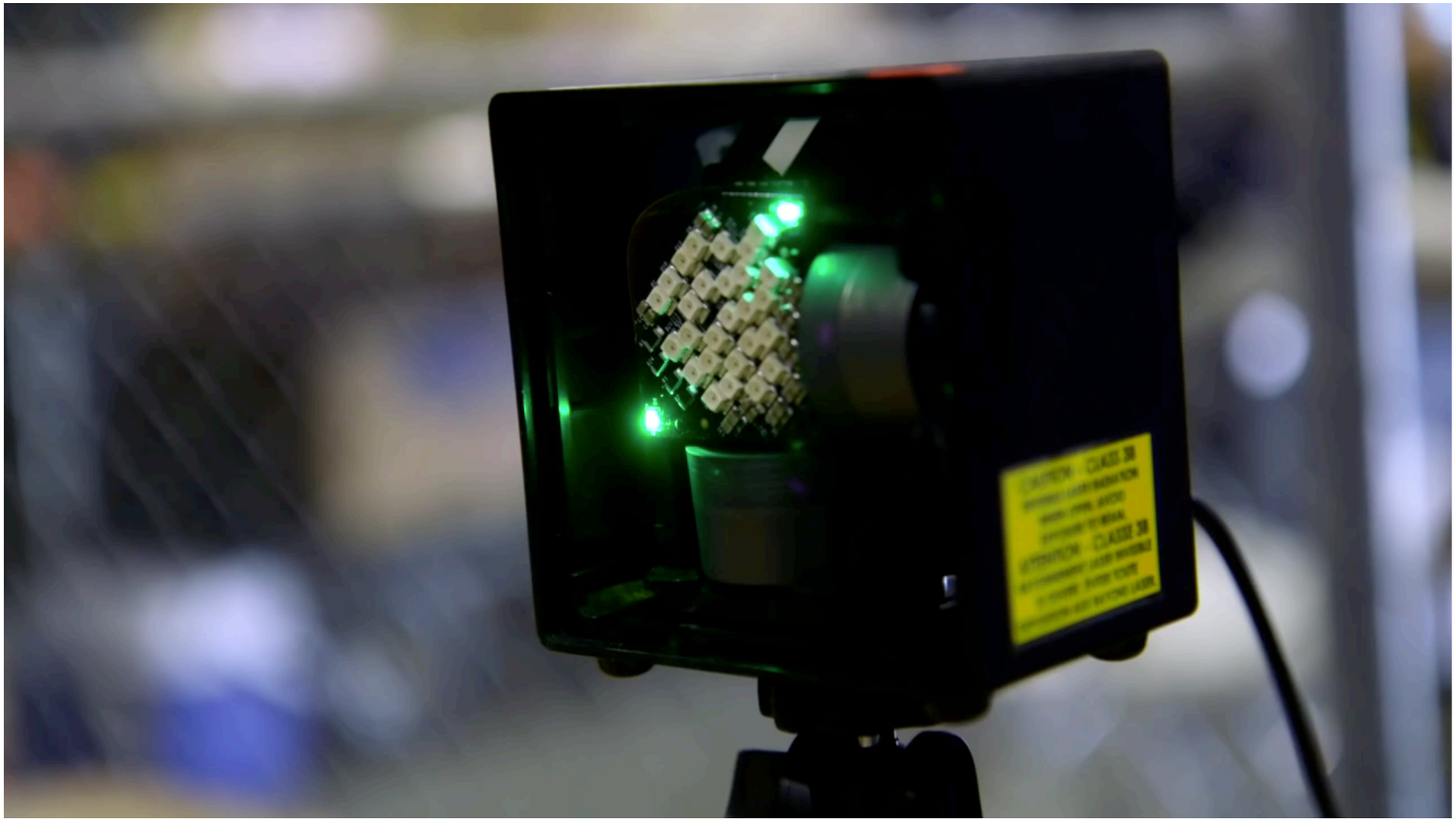
Outside-in hybrid tracking system



# Optical Tracking

**Valve's SteamVR "Lighthouse" (HTC Vive)**

Outside-in hybrid tracking system



# Optical Tracking

**Valve's SteamVR "Lighthouse" (HTC Vive)**

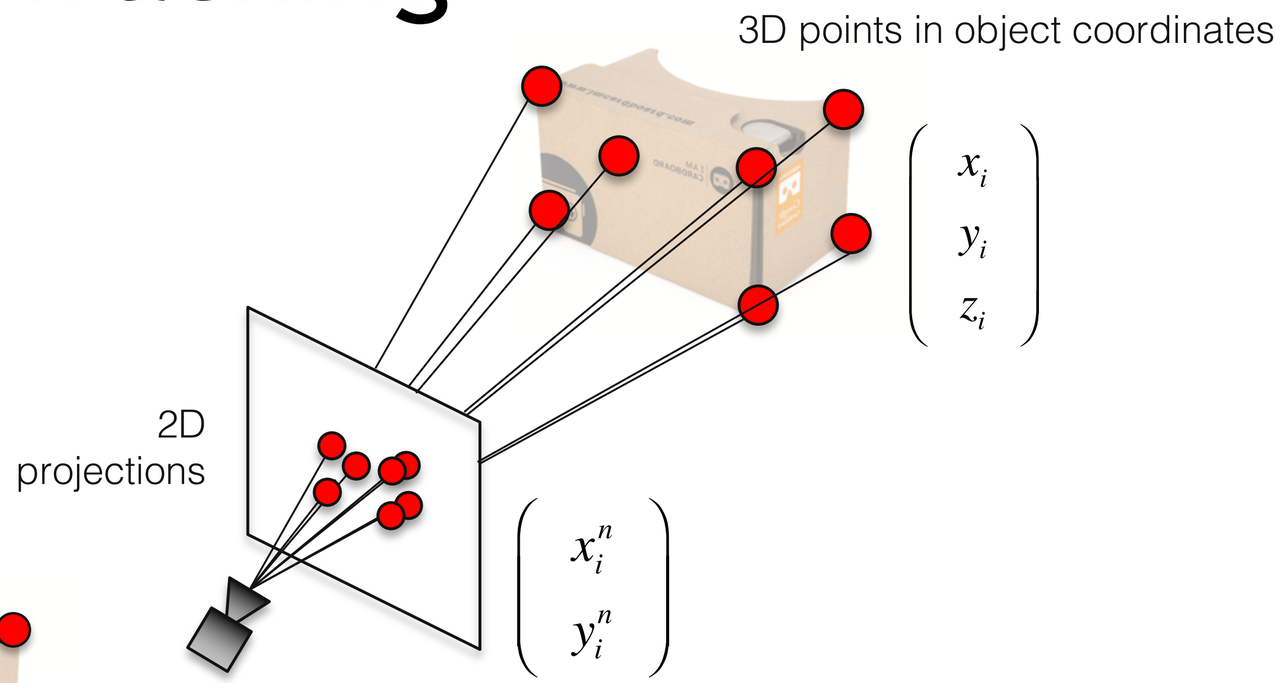
Outside-in hybrid tracking system

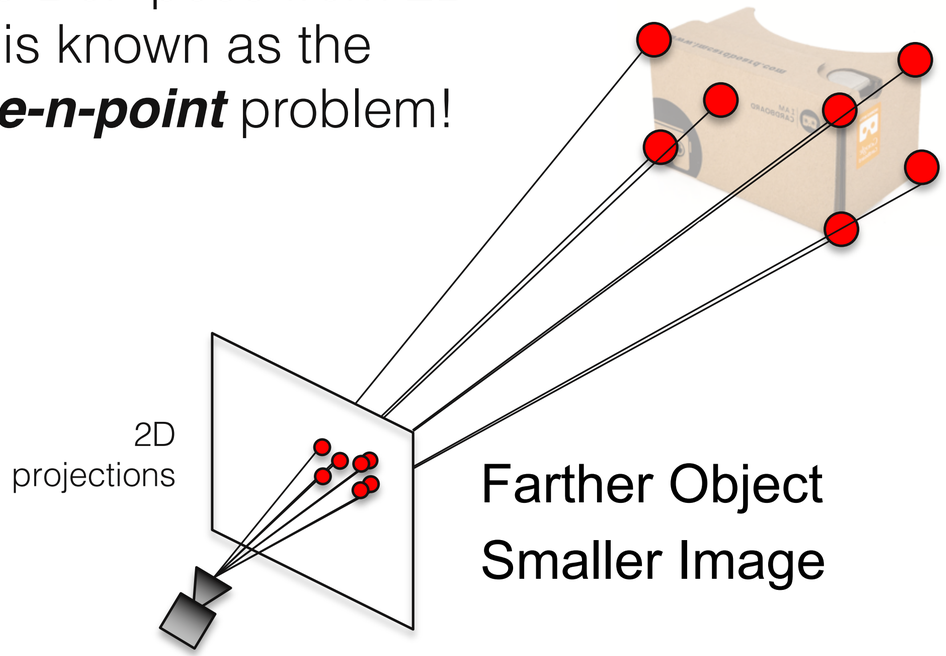
# Optical Tracking

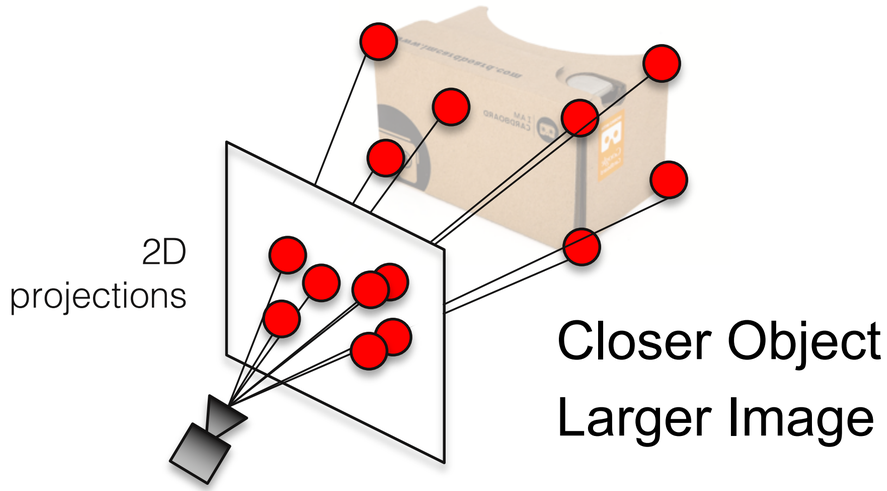
## Outside-in tracking system

- We need to track multiple points with known relative 3D coordinates for pose estimation.

- Estimating 6-DoF pose from 2D projections is known as the ***Perspective-n-point*** problem!



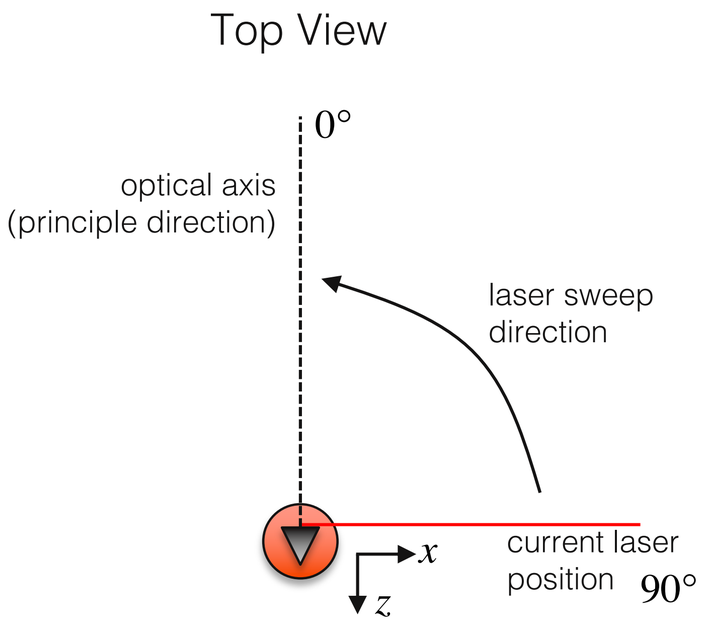



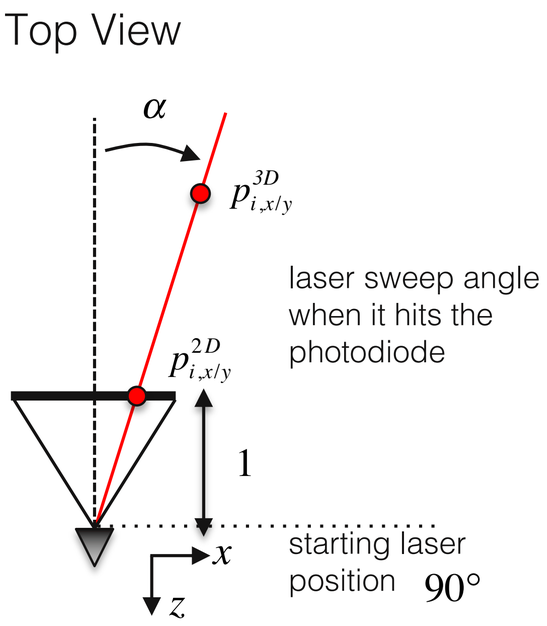



# Optical Tracking

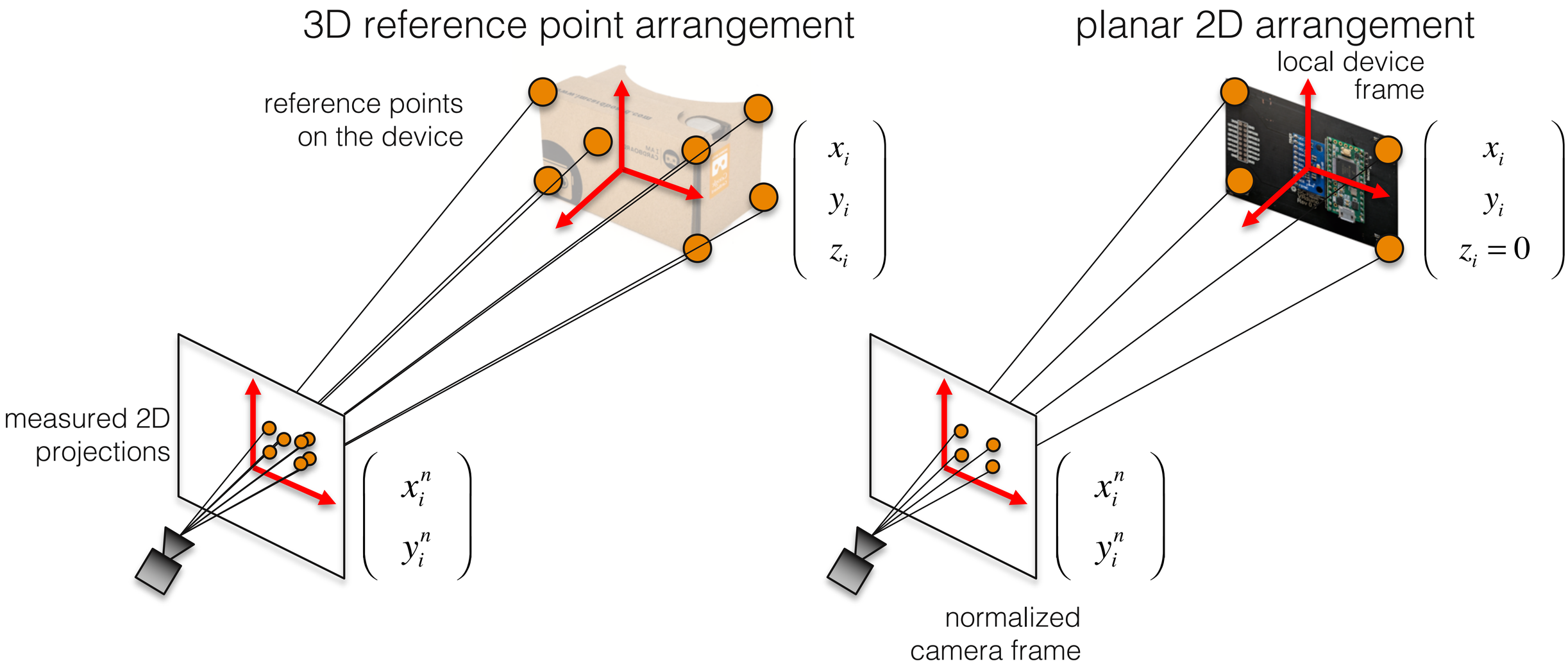
## Outside-in tracking system

- Image formation: We can estimate coordinates of 2D projection of 3D photodiode, i.e., 2D imaging from IR laser



# Optical Tracking

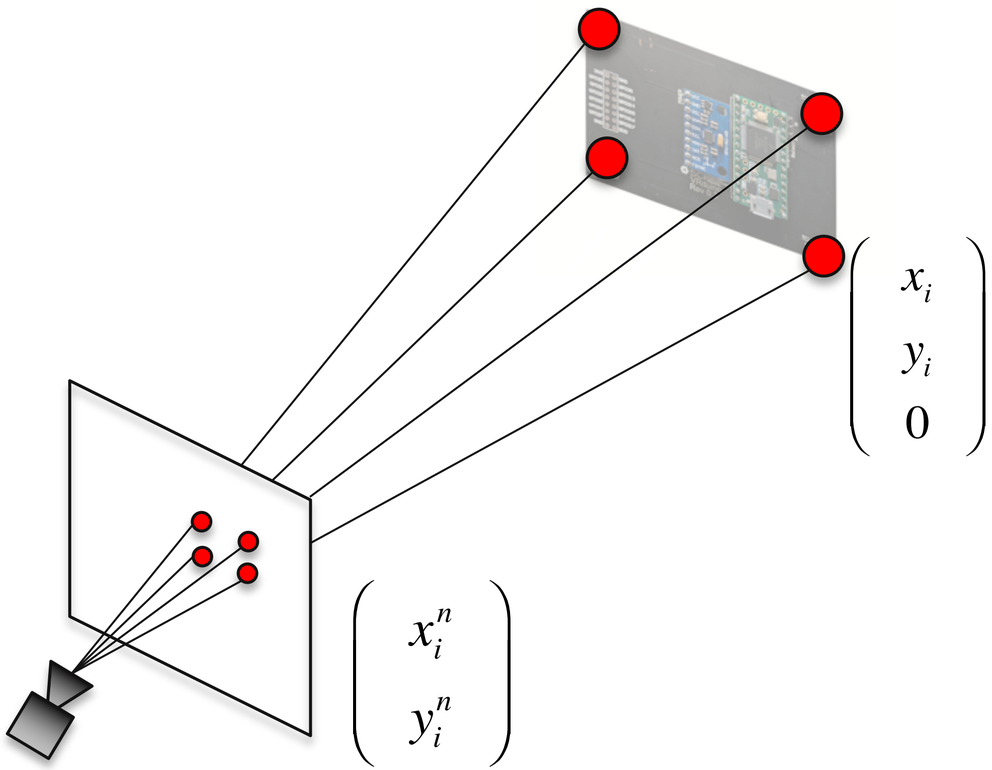


# Optical Tracking

1. transform 3D point into view space:

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

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




2. perspective divide:

$$\begin{pmatrix} x_i^n \\ y_i^n \end{pmatrix} = \begin{pmatrix} \frac{x_i^c}{w_i^c} \\ \frac{y_i^c}{w_i^c} \end{pmatrix}$$

# Optical Tracking

3. estimate posewith linear homography method

rotation R translation T

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

$H$

let's call this "homography matrix"

Any homography matrix has only 8 degrees of freedom – can scale matrix by s and get the same 3D-to-2D mapping

$$\begin{pmatrix} x_i^n \\ y_i^n \end{pmatrix} = \begin{pmatrix} \frac{x_i^c}{w_i^c} \\ \frac{y_i^c}{w_i^c} \end{pmatrix} = \begin{pmatrix} \frac{sh_1 x_i + sh_2 y_i + sh_3}{sh_7 x_i + sh_8 y_i + sh_9} \\ \frac{sh_4 x_i + sh_5 y_i + sh_6}{sh_7 x_i + sh_8 y_i + sh_9} \end{pmatrix} = \begin{pmatrix} \frac{\cancel{s}(h_1 x_i + h_2 y_i + h_3)}{\cancel{s}(h_7 x_i + h_8 y_i + h_9)} \\ \frac{\cancel{s}(h_4 x_i + h_5 y_i + h_6)}{\cancel{s}(h_7 x_i + h_8 y_i + h_9)} \end{pmatrix}$$

# Optical Tracking

## 3. estimate pose with linear homography method

estimate a scaled version of the tomography matrix, where $h_9 = 1$

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

estimate these 8 homography matrix elements!

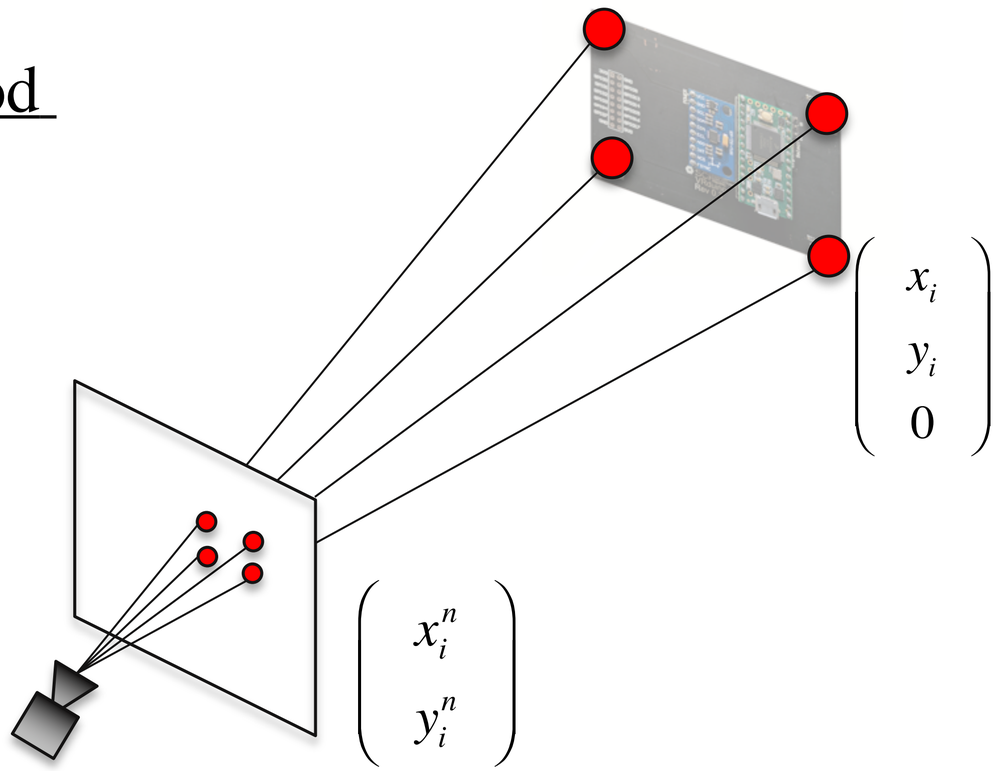
# Optical Tracking

3. estimate pose with linear homography method

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

homography matrix with

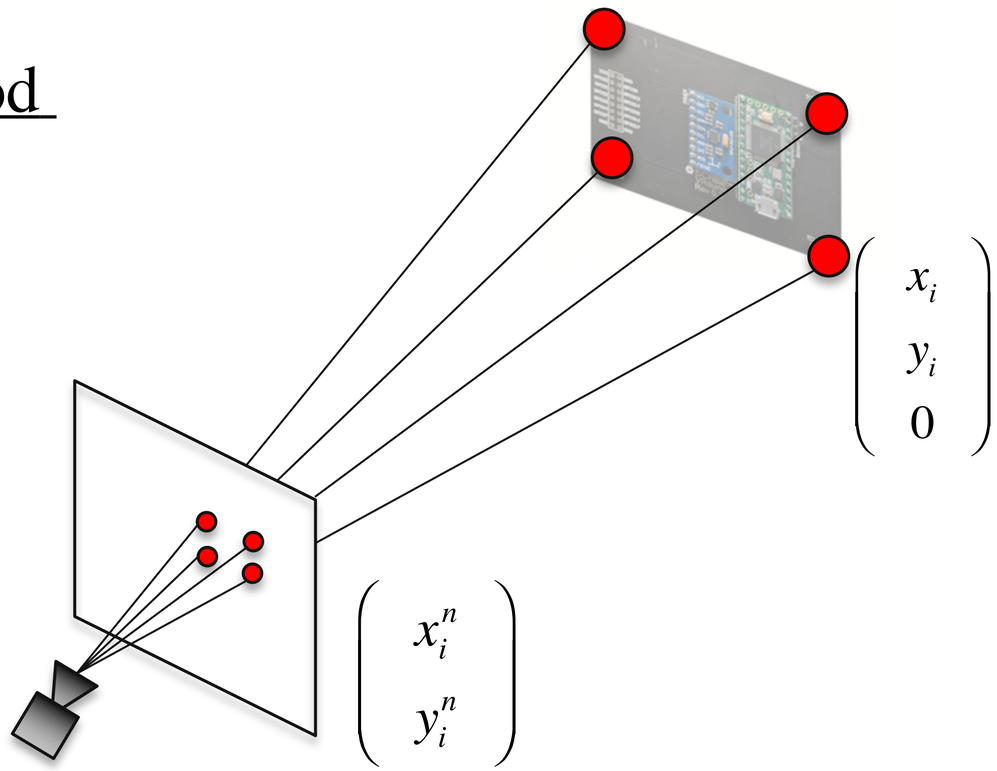
8 unknowns!



# Optical Tracking

3. estimate pose with linear homography method

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



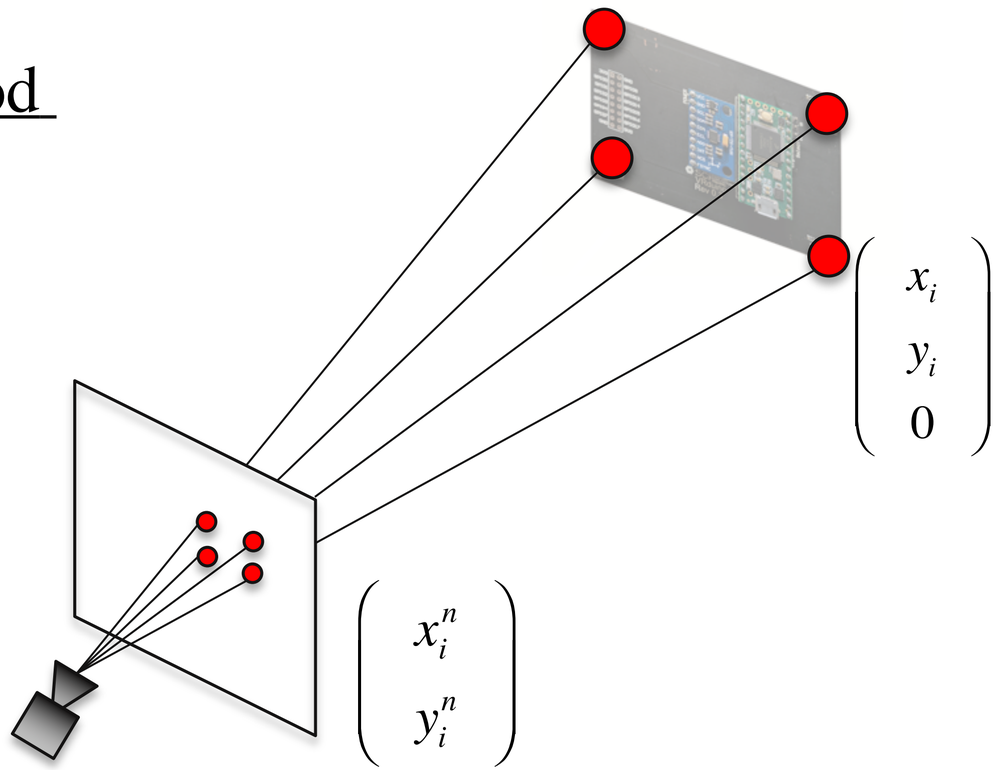
# Optical Tracking

3. estimate pose with linear homography method

**Can be rewritten as in equation form as:**

$$\boxed{h_1} x_i + \boxed{h_2} y_i + \boxed{h_3} - \boxed{h_7} x_i \boxed{x_i^n} - \boxed{h_8} y_i \boxed{x_i^n} = \boxed{x_i^n}$$

$$\boxed{h_4} x_i + \boxed{h_5} y_i + \boxed{h_6} - \boxed{h_7} x_i \boxed{y_i^n} - \boxed{h_8} y_i \boxed{y_i^n} = \boxed{y_i^n}$$



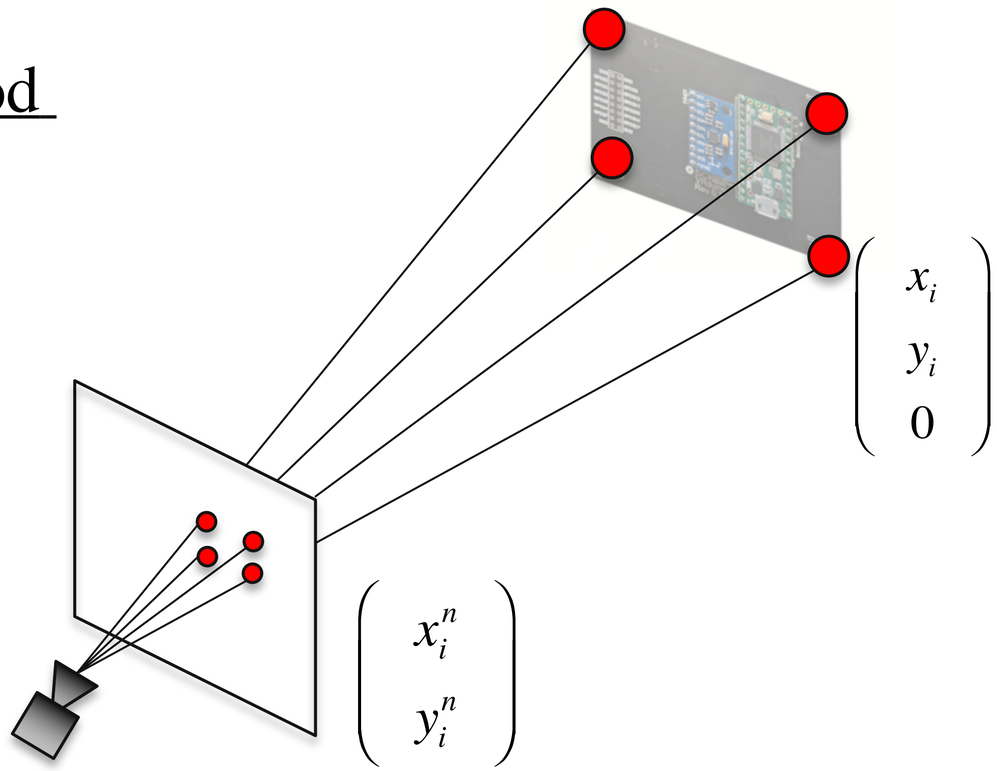

- 8 unknowns (red) but only 2 measurements (blue) per 3D-to-2D point correspondence.
- Need at least 4 point correspondences to get to invertible system with 8 equations & 8 unknowns!

# Optical Tracking

3. estimate pose with linear homography method

**Solve linear system of equation:** $Ah = b$

$$\underbrace{\begin{pmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & -x_1 x_1^n & -y_1 x_1^n \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -x_1 y_1^n & -y_1 y_1^n \\ x_2 & y_2 & 1 & 0 & 0 & 0 & -x_2 x_2^n & -y_2 x_2^n \\ 0 & 0 & 0 & x_2 & y_2 & 1 & -x_2 y_2^n & -y_2 y_2^n \\ x_3 & y_3 & 1 & 0 & 0 & 0 & -x_3 x_3^n & -y_3 x_3^n \\ 0 & 0 & 0 & x_3 & y_3 & 1 & -x_3 y_3^n & -y_3 y_3^n \\ x_4 & y_4 & 1 & 0 & 0 & 0 & -x_4 x_4^n & -y_4 x_4^n \\ 0 & 0 & 0 & x_4 & y_4 & 1 & -x_4 y_4^n & -y_4 y_4^n \end{pmatrix}}_{A} \underbrace{\begin{pmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ h_5 \\ h_6 \\ h_7 \\ h_8 \end{pmatrix}}_{h} = \underbrace{\begin{pmatrix} x_1^n \\ y_1^n \\ x_2^n \\ y_2^n \\ x_3^n \\ y_3^n \\ x_4^n \\ y_4^n \end{pmatrix}}_{b}$$



# Optical Tracking

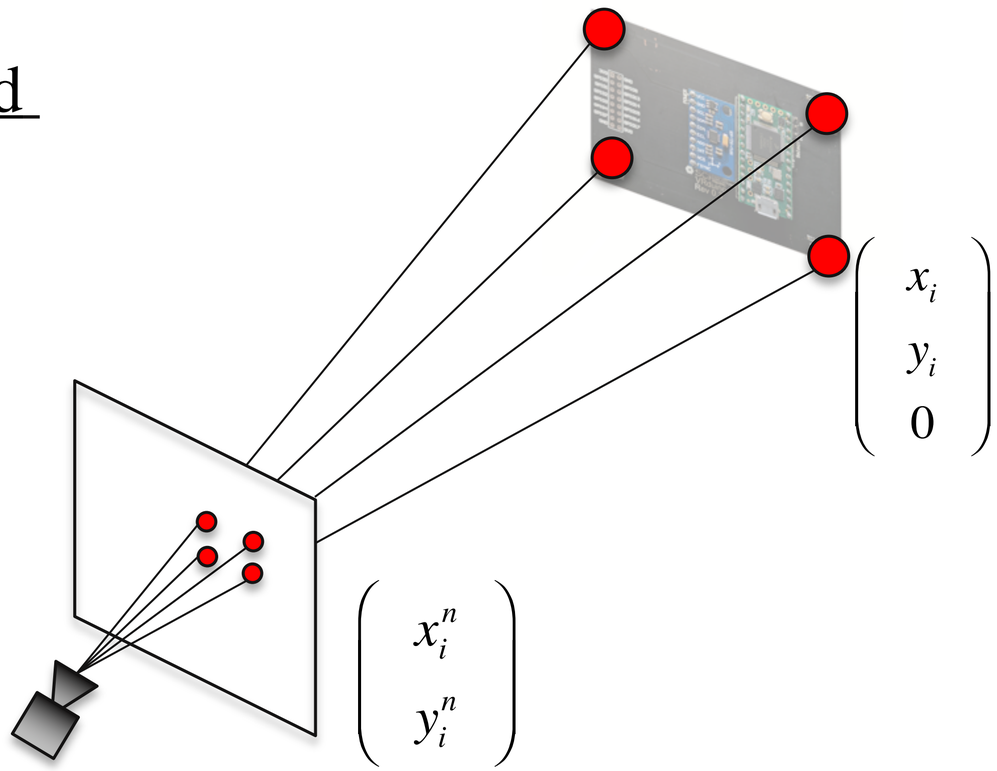
## 3. estimate posewith linear homography method

**Recovering scale**

normalize homography to have approx. unit-length columns for the rotation part, such that:

$$\sqrt{r_{11}^2 + r_{21}^2 + r_{31}^2} \approx 1, \quad \sqrt{r_{12}^2 + r_{22}^2 + r_{32}^2} \approx 1$$

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




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

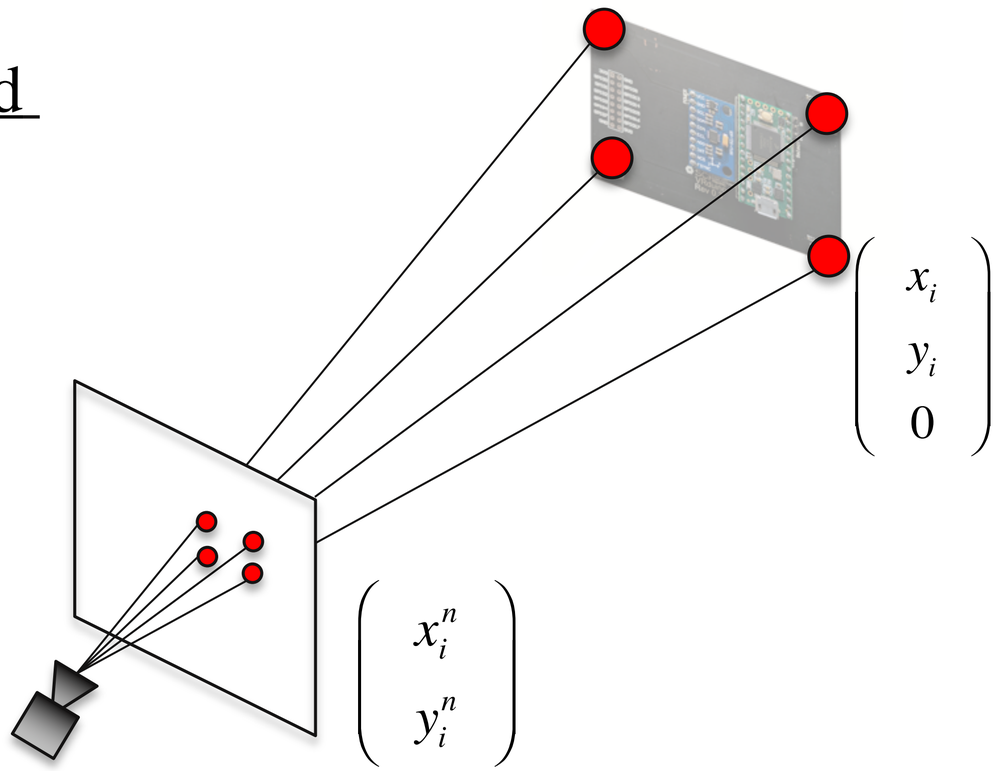
# Optical Tracking

3. estimate posewith linear homography method

**Recovering Position (translation)**

just computed this

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




$$\boxed{t_x = sh_3, \quad t_y = sh_6, \quad t_z = -s}$$

# Optical Tracking

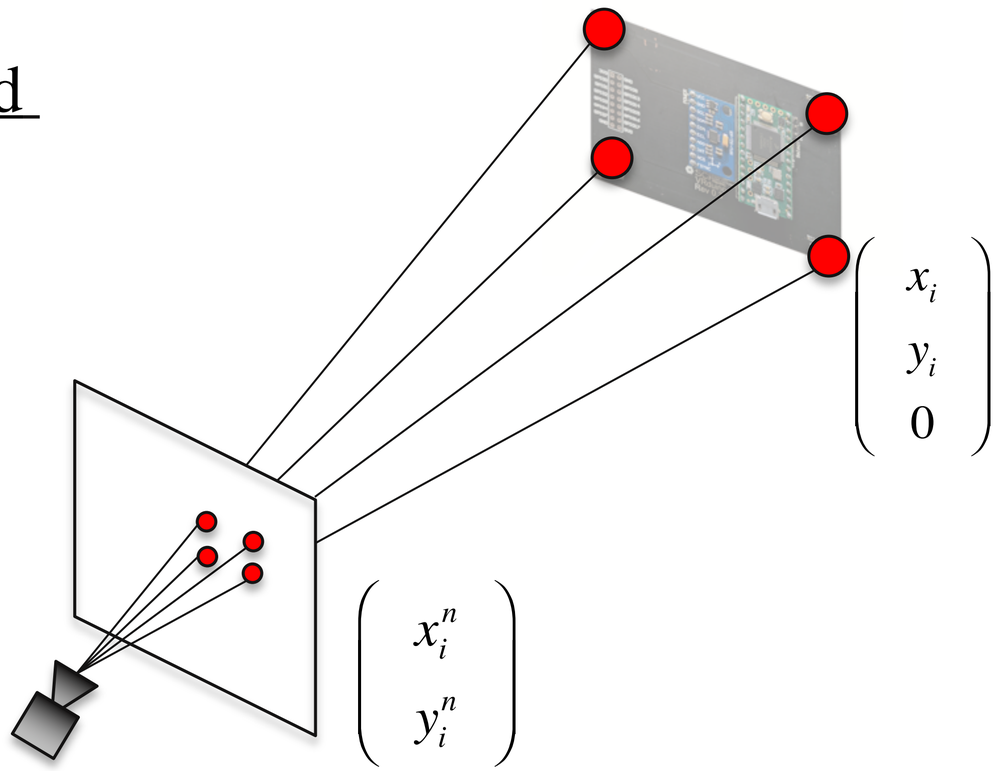
3. estimate posewith linear homography method

**Recovering Orientation (Rotation)**

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

$$\tilde{r}_2 = \begin{pmatrix} h_2 \\ h_5 \\ -h_8 \end{pmatrix} - \left( r_1 \bullet \begin{pmatrix} h_2 \\ h_5 \\ -h_8 \end{pmatrix} \right) r_1, \quad r_2 = \frac{\tilde{r}_2}{\|\tilde{r}_2\|_2}$$

$$r_3 = r_1 \times r_2$$




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

# Optical Tracking

4. temporal filtering

- 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 $\alpha$ → less filtering, larger $\alpha$ → more smoothing

# Optical Tracking

<u>Final algorithm in loop</u>

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

Thank You !

Questions ?