


Calibrating IPTs

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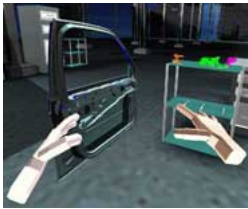
Overview

- Effect of erroneous camera position
- Sources of error
- Tracking system errors
- Correcting distortions

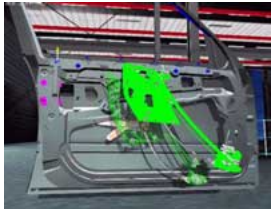
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My background


- Virtual prototyping:
 - Assembly simulation
 - Styling review
 - Scientific immersive visualization
 - Ergonomics




Introduction




Error effects



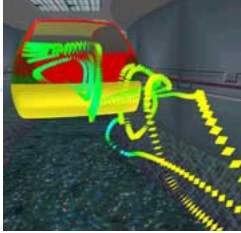
Error sources




Tracking errors



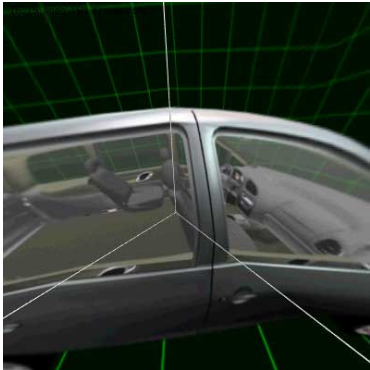
Correcting distortions



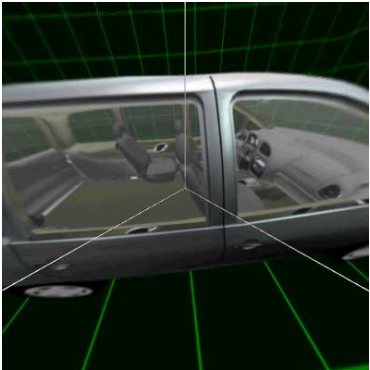


Effect of erroneous camera position

- Cave/Powerwall: image distortion
- HMD/Boom: precise manipulation/positioning



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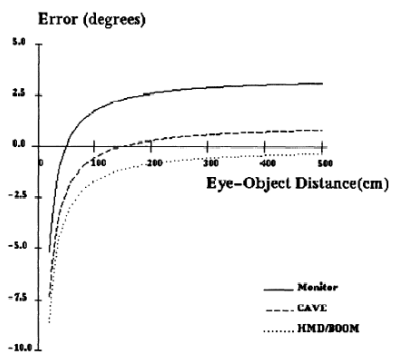
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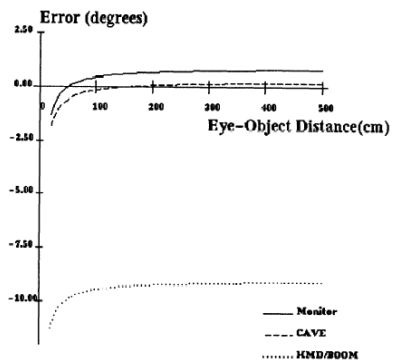


HMD/Boom vs. Cave/Powerwall

- Difference: projection plane moves / doesn't move
- Error analysis:



Angular error, head displacement



Angular error, head rotation



Different effects on different displays

- Translational camera displacement: HMD is usually better (has less error)
- Rotational camera displacement: Cave is better
- Problem in the Cave: image distortion
- Problem in the HMD: virtual hand doesn't appear where user knows his real hand is

Sources of Error

- Objective:
 1. Delay
 2. Transformation pipeline
 3. Minor other sources
 4. Tracking system
- Subjective:
 - Reports from users, but ...
 - Uncharted area!

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Delay (latency / lag)

- Time span from user action until display update
- Types of lag
 - Device
 - Transport
 - Software
 - Synchronisation
- Latency pipeline:

The diagram illustrates the latency pipeline with the following components and values:

- Tracking-System:** Frequency 60-240 Hz, latency ~10 msec.
- Filter:** Frequency 20 Hz, latency 20.
- Ethernet:** Frequency 20 Hz, latency 2.
- Application:** Frequency 20 Hz, latency 50. Sub-components: Comm., main, Renderer.
- Video hardware:** Frequency 60-120 Hz, latency 0-16.
- Monitor:** Frequency 60-120 Hz, latency 16.


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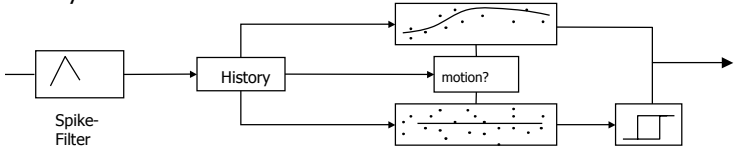
- Human factors
 - Effect of latency

Latency / millisec	Effect on user
5	Noticeable
30	User performance decreases (possibly "simulator sickness")
500	Immersion collapses
 - Head motion
 - Typically 10 cm/sec and 20 deg/sec
 - Max. most of the time 50 cm/sec and 50 deg/sec
 - Peak 1000 deg/sec

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- What you should do against latency
 - Device:
 - "Continuous mode" for device and device server
 - Activate only those sensors the app really uses
 - Time-critical computing
 - Predictive LOD estimation for constant frame
 - CFD visualization (streamlines, isosurface, ...)
 - Predictive tracker filtering!
 - Kalman
 - Autoregression
 - Polynomial fit



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Transformation errors

- User model

Tracker CS

Head rotation center

Cyclops's eyes

Sensor

M_{rs}

M_{er}

T_l

T_r

right

left

camera

hands

cart

$$M_e = T_{l|r} M_{er} M_{rs} M_s$$

M_s = current sensor position
 M_e = viewpoint transf. for eye

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Where is the display?

Cave

Tracker CS

HMD

M_{ld}

M_{rd}

D

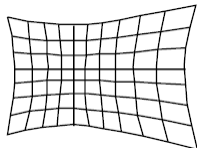
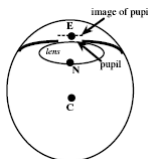
M_{xd} = trf. from left/right eye to display
 D = display geometry

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Minor error sources

- Optical distortion by the display
 - Possible solution: render twice





- Eye tracking?
 - Error is negligible, if projection center = eye center







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Tracking system technologies

- Electro-magnetic
- Mechanical
- Optical
- Acoustic
- Inertia-sensing
- GPS
- Computer-vision based
- ...


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■ Prices (2001)

System	Approx. Price (EUR)
Ascension Flock-of-Birds (ERT)	10,000
Polhemus Fastrak (long ranger)	13,000
Intersense IS600	19,000
MotionAnalysis	100,000 – 300,000

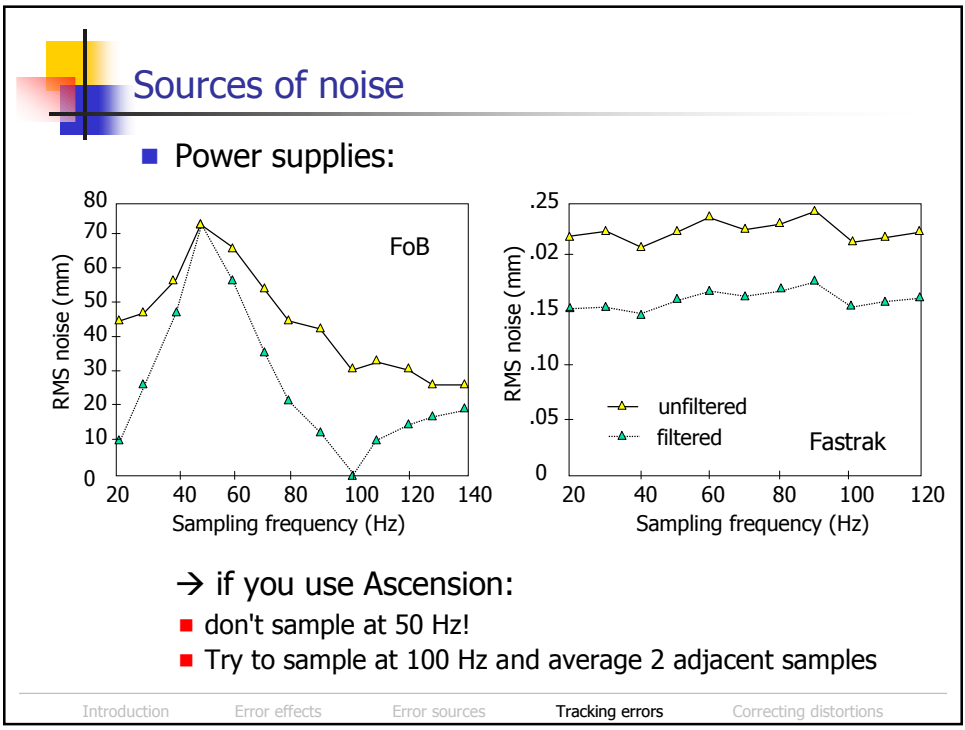
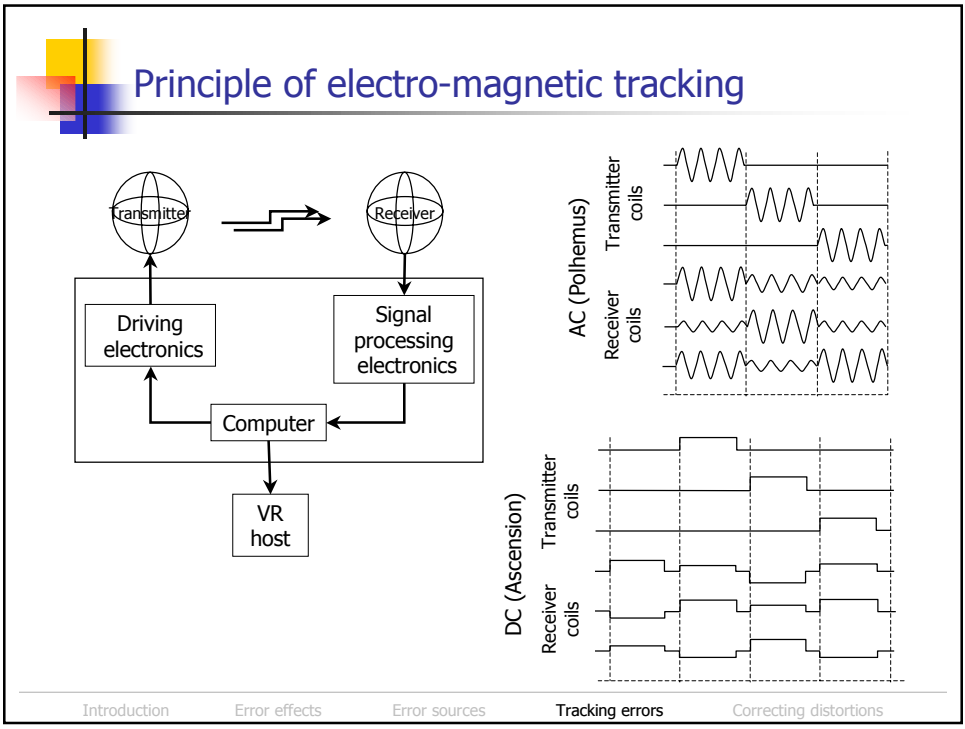
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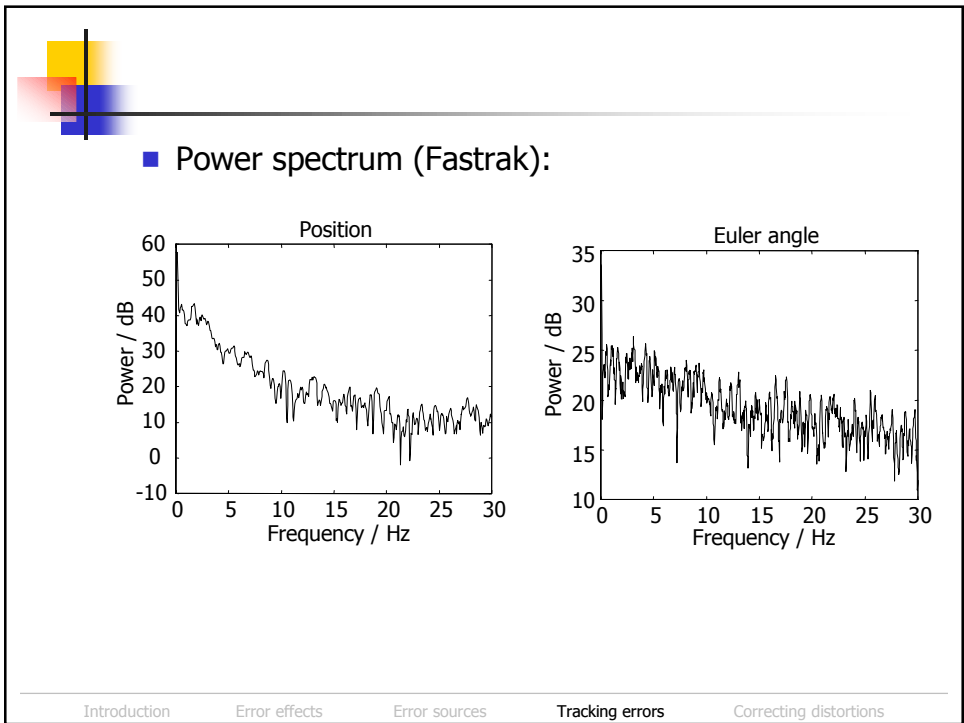
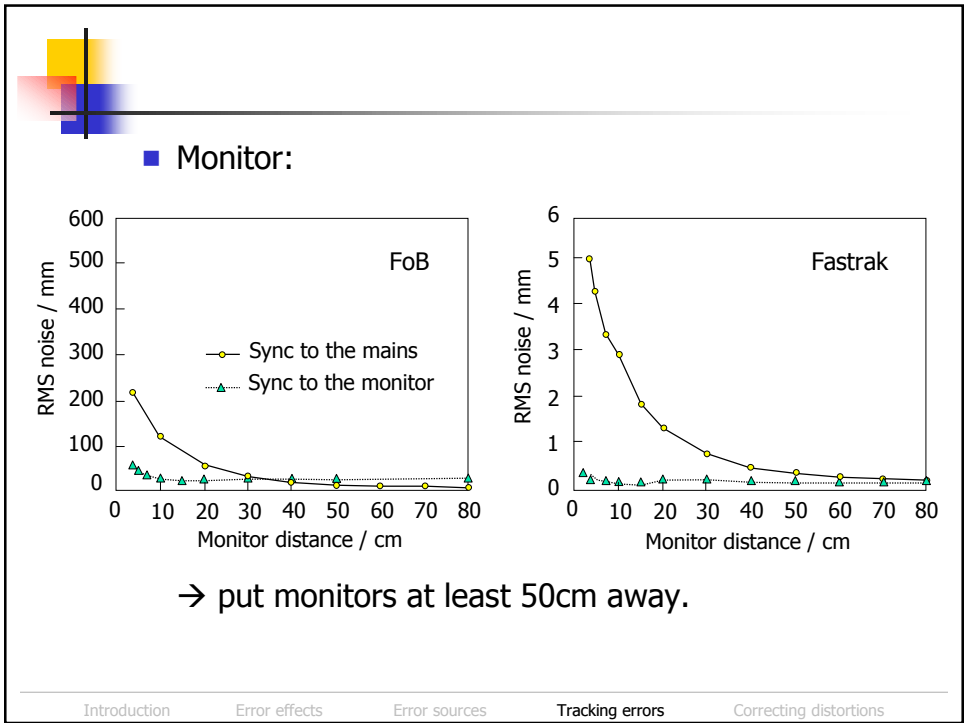


Tracking system errors

- Static:
 - Mis-alignment
 - Distortions
- Dynamic:
 - Noise
 - Drift
 - Drop-outs

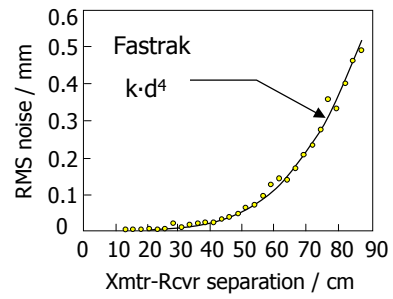
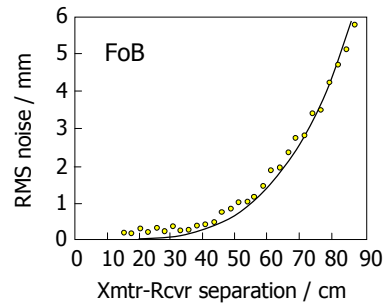
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- Distance between receiver and transmitter:



- place the transmitter close to the work area
- use a long-range transmitter



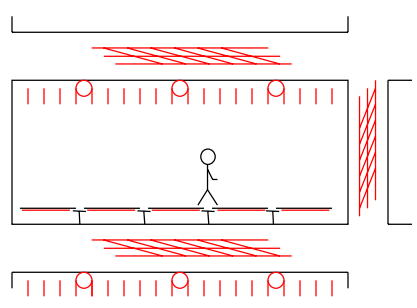
- Other sources of noise:

- Receiver / transmitter cables
- Cell phones

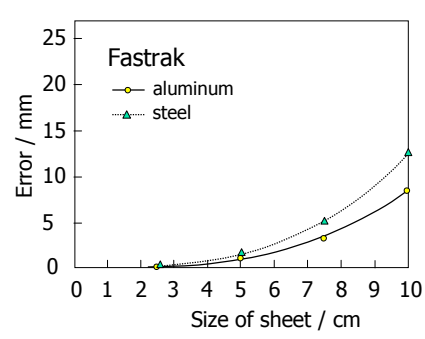
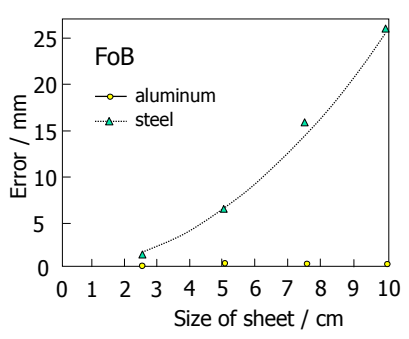
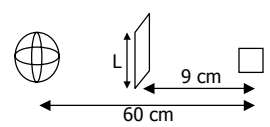


Sources of distortion

- Where is all the metal hidden?
 - Floor covering (and ceiling of next lower floor)
 - Ceiling (lamps, covering, air conditioning, ...)
 - Walls (steel grid of reinforced concrete)
 - Monitors (coils), computers (shielding), projectors



Effect of size of different sheet metal:



■ Some measurements in real labs:

2x2x1 m³

1x1x2 m³

Polhemus Fastrak & Longranger

Ascension FoB + ERT

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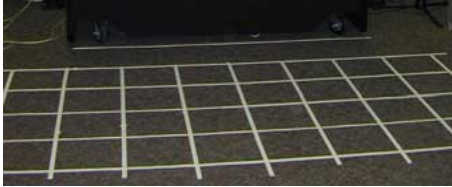

■ ... and in our new cave:

2.5 x 2.5 x 2 m³

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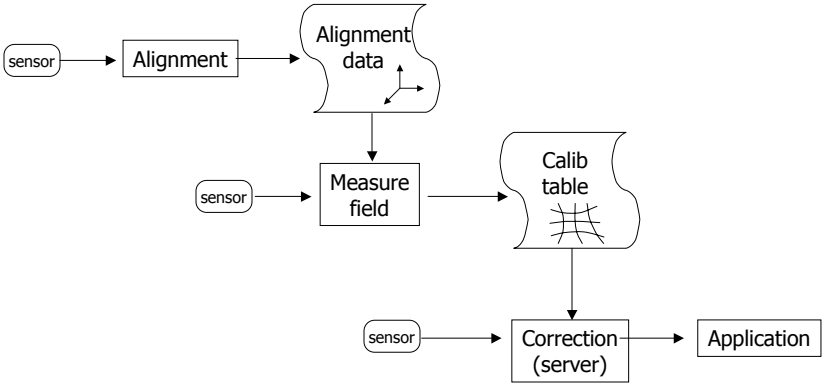
Correcting distortions

- Ingredients for building a calibration table:
 - Markers on the floor, possibly on paper
 - Metal-free holding device for the sensor, possibly several sensors
 - Calibration measurement tool
- Time needed:
 - Preparation ≈ 1-2 hours
 - Measurement ≈ 30 minutes

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Data flow:



```

    graph LR
      S1(sensor) --> A[Alignment]
      A --> AD(Alignment data)
      S2(sensor) --> MF[Measure field]
      AD --> MF
      MF --> CT(Calib table)
      S3(sensor) --> CS[Correction server]
      CT --> CS
      CS --> App[Application]
  
```

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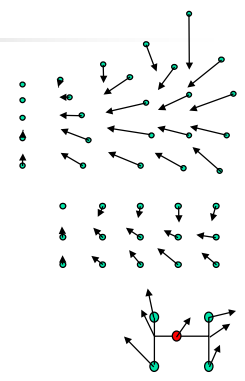
Correction algorithms

- Problem: interpolation
- Verified empirically:
 - Position error does not depend on sensor orientation
 - Orientation error depends on sensor position only
- Approaches:
 - Look-up tables
 - Polynomial interpolation/approximation
 - B-spline volumes
 - Shape functions
 - Radial basis functions (Hardy's Multi-Quadric)



Lookup table

- Given: measured points and errors
- Resample into regular grid using Gauss kernel
$$v_Q = \sum_P v_P e^{-\frac{|P-Q|^2}{d^2}}$$
- Correction at run-time = trilinear interpolation
- Is the grid dense enough? Test: calculate correction vector for known measured points using trilinear interpolation, compare with the measured error vectors.
- Orientations: use quaternions and spherical linear interpolation





Polynomial approximation

- Polynomial fit:

$$f(x, y, z) = \sum_{j=1}^R c_j x^{s_j} y^{t_j} z^{u_j}$$

$$c_j \in \mathbb{R}^3, \quad 0 \leq s_j + t_j + u_j \leq r$$

$$R = (r+1)(r+2)(r+3)/6$$

- Minimize

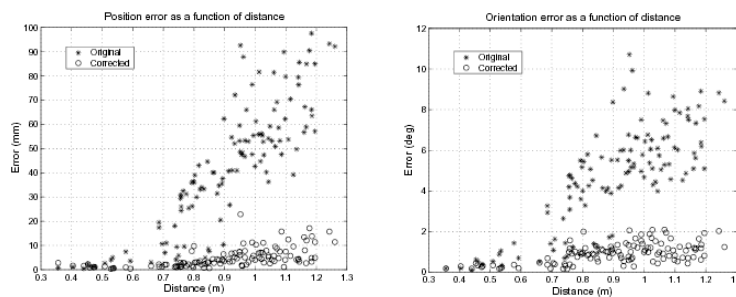
$$S = \sum_{j=1}^N \|e^j - f(P^j)\|$$

by least squares method

- Rotations: exactly analogously with $g(x, y, z)$



- Result (Ikits, Brederson, Hansen, Hollerbach):





Hardy's Multi-Quadric (HMQ)

Approach for translation

$$f: \mathbb{R}^3 \rightarrow \mathbb{R}^3$$

$$f(\mathbf{P}) = \sum \mathbf{A}_i \omega_i(\mathbf{P}) \quad , \quad \mathbf{A}_i \in \mathbb{R}^3$$

$$\omega_i(\mathbf{P}) = \left[(\mathbf{P} - \mathbf{P}_i)^2 + R^2 \right]^\mu \quad \text{"radial basis functions"}$$

$$\mu_i = \left\{ \frac{1}{2}, \frac{1}{4}, 2, -\frac{1}{2}, \dots \right\}$$

plug in measured points

$$f(\mathbf{P}_j) = \mathbf{Q}_j \quad , \quad j = 1, \dots, N$$

yields 3 LES

$$\begin{pmatrix} \omega_1(\mathbf{P}_1) & \dots & \omega_N(\mathbf{P}_1) \\ \vdots & & \vdots \\ \omega_1(\mathbf{P}_N) & \dots & \omega_N(\mathbf{P}_N) \end{pmatrix} \begin{pmatrix} \mathbf{A}_1 \\ \vdots \\ \mathbf{A}_N \end{pmatrix} = \begin{pmatrix} \mathbf{Q}_1 \\ \vdots \\ \mathbf{Q}_N \end{pmatrix}$$



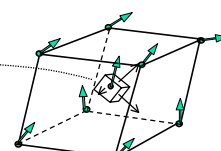
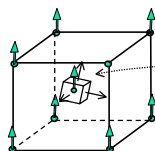
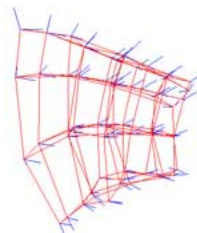
■ Orientation:


- Should still correct, even in cave:
 - Vertical parallax
 - Hand tracking (virtual hand, pointer, ...)
- Interpolation function $g: \mathbb{R}^3 \rightarrow \mathbb{R}^6$
- Calibration table contains measured ori M_p^0 of "zero orientation"
- To correct orientation M_p^{measured} at point P compute

$$M_p^{\text{correct}} = M_p^{0^{-1}} \cdot M_p^{\text{measured}}$$

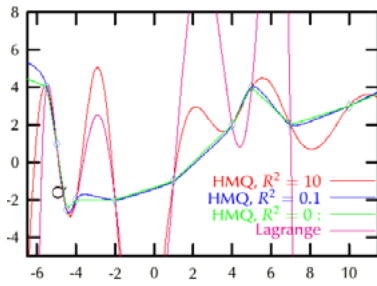
with

$$M_p^0 = g(\mathbf{P})$$






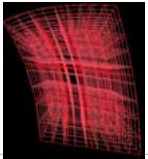
- Interpolation of orientations:
 - Quaternions $g : \mathbb{R}^3 \rightarrow \mathbb{R}^4$
 - 2 vectors $g : \mathbb{R}^3 \rightarrow \mathbb{R}^6$
- Normalize $g(P)$
- The optimal R^2 :
 - No theoretical results
 - My experience: $[0.1, 100]$ is good for enough points in 3D

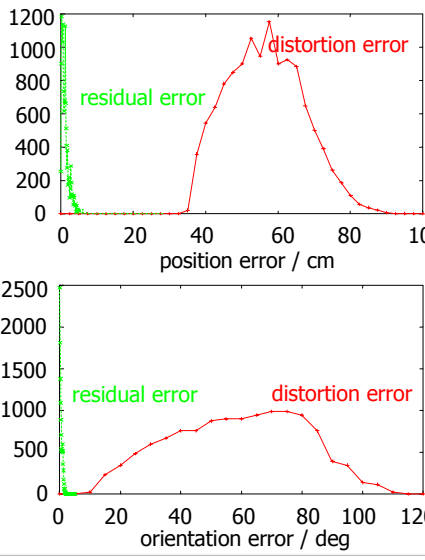


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- Performance of HMQ:
 - Model distortion by analytical functions
 - Compute HMQ
 - Plot error distribution of "distortion functions"
 - Plot error after correction with HMQ
 - More plots at <http://web.informatik.uni-bonn.de/~zach/papers/diss.html>





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Advantages of HMQ

- Fast: ca. 0.5 millisecc with 200 samples
- Arbitrary point clouds
 - Non-rectangular workspace (e.g., real mock-up plus VR display)
 - Semi-automatic calibration at run-time



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Literature

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URLs

- <http://web.informatik.uni-bonn.de/~zach/index.html>
- <http://web.informatik.uni-bonn.de/~zach/papers/diss.html>
- <http://www.igd.fhg.de/igd-a4/projects/ideal/ideal.html>
- <http://www.ncsa.uiuc.edu/~kindr/emtc.html>
- <http://www.polhemus.com/>
- <http://www.ascension-tech.com/>