Calibrating IPTs

Dr. Gabriel Zachmann
University Bonn, Germany
zach@cs.uni-bonn.de
web.informatik.uni-bonn.de/~zach

Overview

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

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

Effect of erroneous camera position

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

Delay (latency / lag)

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

![Latency Pipeline Diagram]

- Tracking System
- Filter
- Rendering
- Video Hardware

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60-240 Hz 60-120 Hz 60-120 Hz

- 0-16
- 16
- 20 Hz
- 50
- 2
- 20
- ~10 msec
Human factors

- **Effect of latency**

<table>
<thead>
<tr>
<th>Latency / millisec</th>
<th>Effect on user</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Noticeable</td>
</tr>
<tr>
<td>30</td>
<td>User performance decreases (possibly &quot;simulator sickness&quot;)</td>
</tr>
<tr>
<td>500</td>
<td>Immersion collapses</td>
</tr>
</tbody>
</table>

- **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

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
Transformation errors

- User model

\[ M_e = T_{l/r} M_{r/e} M_s T_s \]

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

Where is the display?

\[ M_{id} = \text{trf. from left/right eye to display} \]
\[ D = \text{display geometry} \]
Minor error sources

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

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

Tracking system technologies

- Electro-magnetic
- Mechanical
- Optical
- Acoustic
- Inertia-sensing
- GPS
- Computer-vision based
- ...
Prices (2001)

<table>
<thead>
<tr>
<th>System</th>
<th>Approx. Price (EUR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ascension Flock-of-Birds (ERT)</td>
<td>10,000</td>
</tr>
<tr>
<td>Polhemus Fastrak (long ranger)</td>
<td>13,000</td>
</tr>
<tr>
<td>Intersense IS600</td>
<td>19,000</td>
</tr>
<tr>
<td>MotionAnalysis</td>
<td>100,000 – 300,000</td>
</tr>
</tbody>
</table>

Tracking system errors

- **Static:**
  - Mis-alignment
  - Distortions

- **Dynamic:**
  - Noise
  - Drift
  - Drop-outs
Principle of electro-magnetic tracking

Sources of noise

- **Power supplies:**

  
  - if you use Ascension:
    - don't sample at 50 Hz!
    - Try to sample at 100 Hz and average 2 adjacent samples
Monitor:

- put monitors at least 50cm away.

Power spectrum (Fastrak):

- Sync to the mains
- Sync to the monitor

→ put monitors at least 50cm away.
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:

- FoB
  - aluminum
  - steel

- Fastrak
  - aluminum
  - steel
Some measurements in real labs:

- Ascension FoB + ERT
- Polhemus Fastrak & Longranger

... and in our new cave:

- 2.5 x 2.5 x 2 m³
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

Data flow:

- Sensor to Alignment
- Alignment to Alignment data
- Sensor to Measure field
- Measure field to Calibration table
- Calibration table to Correction (server)
- Correction (server) to Application
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
  \[ v_\theta = \sum_p v_pe^{\frac{\|P - Q_p\|^2}{\sigma^2}} \]
- 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:**
  \[
  f(x, y, z) = \sum_{j=1}^{R} c_j x^{s_j} y^{t_j} z^{u_j}
  \]
  \[
  c_j \in \mathbb{R}^3, \quad 0 \leq s_j + t_j + u_j \leq r, \quad R = \frac{(r + 1)(r + 2)(r + 3)}{6}
  \]

- Minimize
  \[
  S = \sum_{j=1}^{N} \| e_j - f(P_j) \|
  \]
  by least squares method

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

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

- Position error as a function of distance
- Orientation error as a function of distance
Hardy's Multi-Quadric (HMQ)

Approach for translation

\[ f : \mathbb{R}^3 \rightarrow \mathbb{R}^3 \]

\[ f(P) = \sum A_i \omega_i(P) , \quad A_i \in \mathbb{R}^3 \]

\[ \omega_i(P) = \left[ \left( P - P_i \right)^2 + R^2 \right]^{\mu} \]

"radial basis functions"

\[ \mu_i = \frac{1}{2}, \frac{1}{4}, 2, \frac{1}{2}, 1 \]

plug in measured points

\[ f(P_j) = Q_j , \quad j = 1, \ldots, N \]

yields 3 LES

\[
\begin{pmatrix}
\omega_1(P_1) & \cdots & \omega_N(P_1) \\
\vdots & \ddots & \vdots \\
\omega_1(P_N) & \cdots & \omega_N(P_N)
\end{pmatrix}
\begin{pmatrix}
A_1 \\
\vdots \\
A_N
\end{pmatrix}
= 
\begin{pmatrix}
Q_1 \\
\vdots \\
Q_N
\end{pmatrix}
\]

- 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 \( M^0_p \) of "zero orientation"
  - To correct orientation \( M^\text{measured}_p \) at point \( P \) compute
    \[ M^\text{correct}_p = M^0_p \cdot M^\text{measured}_p \]
    with
    \[ M^0_p = g(P) \]
- 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

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
Advantages of HMQ

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

Literature

- Carolina Cruz-Neira, Daniel J. Sandin and Thomas A. DeFanti: "Surround-screen projection-based virtual reality: the design and implementation of the CAVE", Siggraph '93, August 2 - 6, 1993, Anaheim, CA USA.
Introduction  Error effects  Error sources  Tracking errors  Correcting distortions

URLs

- http://web.informatik.uni-bonn.de/~zach/index.html
- http://web.informatik.uni-bonn.de/~zach/papers/diss.html
- http://www.ncsa.uiuc.edu/~kindr/emtc.html
- http://www.polhemus.com/
- http://www.ascension-tech.com/