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Kaufmann

Input Devices & Tracking

Hannes Kaufmann

Interactive Media Systems Group (IMS)

Institute of Visual Computing &
Human-Centered Technology

Based on material by Alexander Bornik, Dieter Schmalstieg, Oliver Bimber and Skip Rizzo

Motivation

- Last time: Various VR Application Areas
- VR/AR environment =
  Hardware setup + VR software framework + Application
- Detailed knowledge is needed about
  - Hardware: Input Devices & Tracking, Output Devices, 3D Graphics
  - Software: High-level programm., VR frameworks
  - Human Factors: Usability, Evaluations, Psychological Factors (Perception,…)

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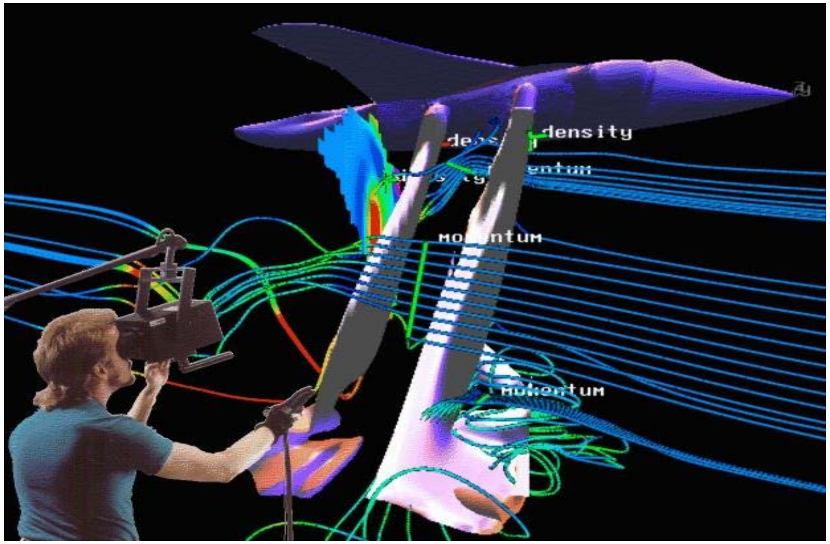
Input devices

- Hardware that allows the user to communicate with the system
- Input device vs. interaction technique (IT) (e.g. zoom)
- Single device can implement many ITs



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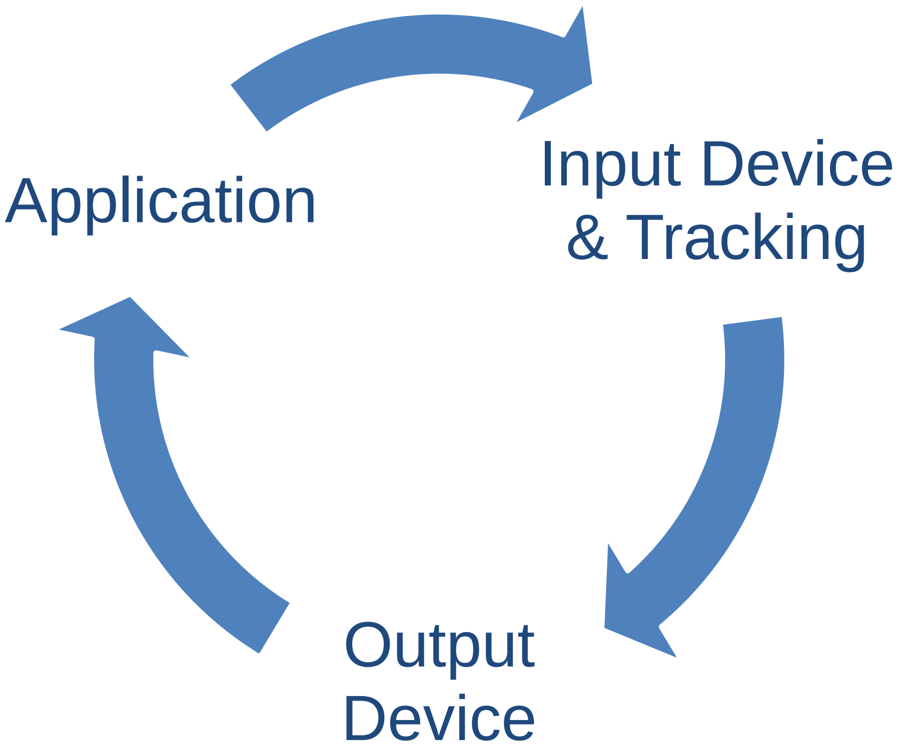
The Interface Problem

Dependencies:



There is **not** a single ideal solution for all applications!

Examples: VR application for children - HMD?, data gloves?
CAD engineer – input by gestures?

How to find a good solution: **Know the possibilities!**

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Input Device Classification

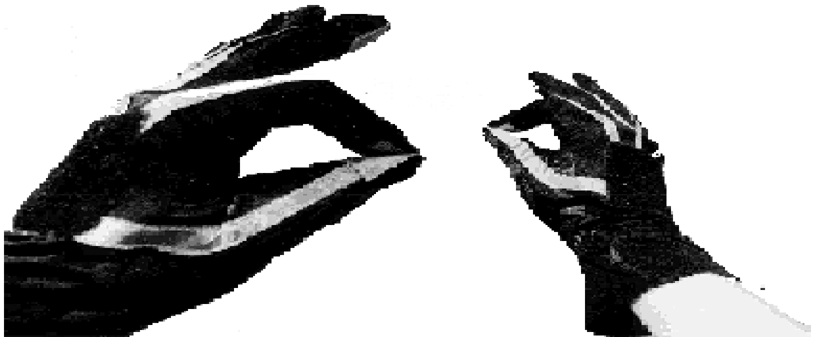
- Discrete – Continuous
- Degrees of Freedom
- Active – Passive
- Technological Principle

Degrees of Freedom (DOF)

- Number of independent values/measurements
- Commonly used:
  - (2DOF -> 2D e.g. mouse)
  - 3DOF -> position
  - 3DOF -> orientation (rotation relative to coordinate system axes): roll / pitch / yaw
  - 6DOF -> position + orientation

Discrete - Continuous

- Discrete / event-based
  - Generate one event at a time based on the user
  - Examples: Keyboard, Pinch Glove (see picture), Buttons
- Continuous / sampled
  - Continuously generate events in isolation (passive) or in response (active) to user action
  - Examples: Trackers, Datagloves
- Hybrids (e.g. mouse)
- Miscellaneous input
  - Speech
  - Gestures
  - Locomotion devices



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Active / Passive Devices

- Purely active input device:
  - Requires user interaction
  - E.g. keyboard, mouse, joystick, dials, sliders
- Passive device:
  - Generate data continuously
  - No input required
  - E.g. motion tracker

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Technological Classification

- Classification by Operating type
  - Architectural / Technological principle
    - E.g. Magnetic, Optical, Inertial,...
  - Regardless of actual implementation
  - How (tracking) data is acquired
- Classification by Implementation
  - Principle of (tracking) data acquisition
  - Physical principle
  - Types of sensors used

Overview

- Desktop Input
- Symbolic Input
- Tracking (6DOF)
  - Criteria
  - Technology
    - Mechanical, Magnetic, Optical, Inertial, Time of Flight, Hybrid
- Haptics
- Locomotion

For all devices:

- Technological Principle
- Technological Advantages & Disadvantages
- Human Factors Advantages & Disadvantages

Desktop Input Devices

Used in Desktop VR:

- Keyboards
- 2D Mice and trackballs
- Joysticks
- Pen based tablets
- 6-DOF devices for the desktop
- Haptics

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Joysticks

- Isotonic Joystick
  - Movement continues until handle pushed back to neutral position
  - Rate control (not position control)
  - Haptics: force-feedback
  - Easy to use

- Isometric Joystick
  - Handle does not move
  - Output varies with force that is applied
  - E.g. laptop trackpoint

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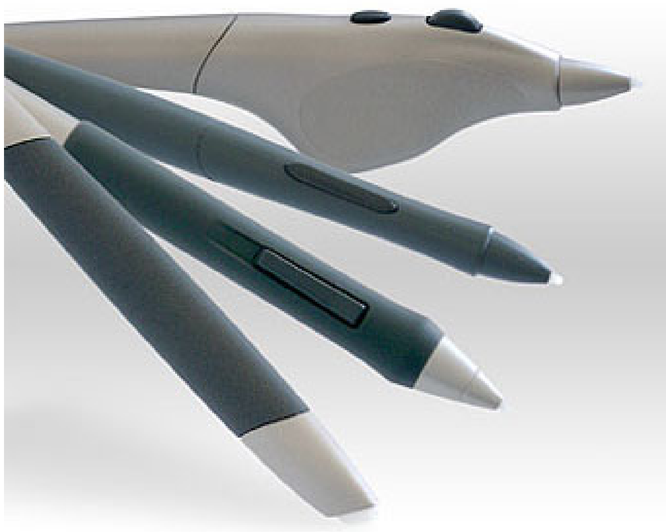
Pen based tablets

e.g. Wacom tablets
- Very precise input
- Absolute input!

Mice/Joystick: relative input



6-DOF Desktop Input Devices

3Dconnexion:

- SpaceMouse
- SpaceBall 5000

Developed for desktop 3D interaction

- CAD
- Used additionally to mouse
- Fine manipulation can be difficult
- Needs time to learn usage
- 3D experts very quick but needs practice
- Not ideal during mobile work

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LEAP Motion

- 2 mono infrared (IR) cameras (300 fps), 3 IR LEDs
- LEDs generate a 3D pattern of dots of IR light
- Processing of point cloud data on PC
- <1 meter distance
- Advantage: High precision
- Disadvantage: Low range, small field of view

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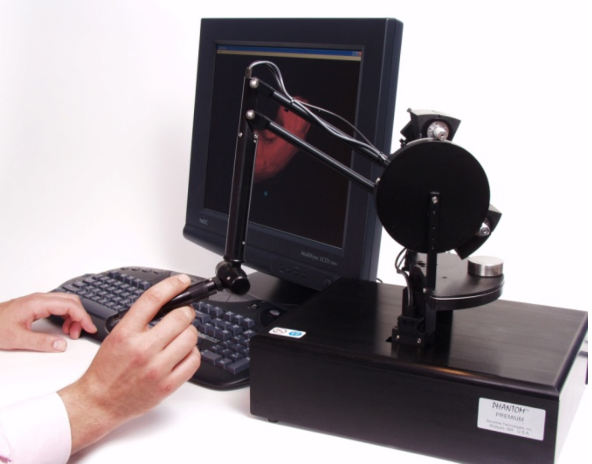
Haptic Input for Desktop VR

Phantom device:

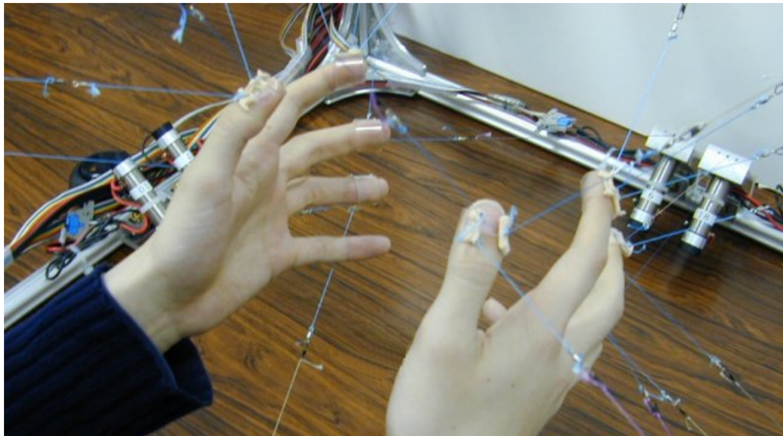
- Accurate 6DOF input
- Mechanical Tracking
- Force Feedback (limited)
- Restricted Area
- Only 1-Point contact !!!



Other Desktop-bound Haptic Devices

- 6-DOF Delta device – spherical knob (Novint Falcon)
- Haptic feeling for all fingers holding the knob
- Not mobile
- Custom made research devices

Video



Symbolic Input Devices

Symbolic Input (Text, Numbers,…) in VR environments

- Design annotation
- Filename entry
- Labeling
- Precise object manipulation
- Parameter setting
- Communication between users
- Markup (highlight, bold,…)

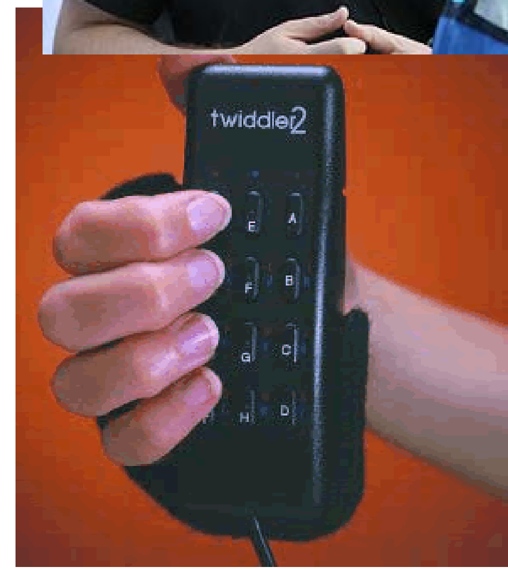
Features of Symbolic Input in 3D

- Desktop devices (e.g. keyboards) usually don‘t work in 3D:
  - Users are standing / physically moving
  - No surface to place a keyboard
  - Difficult or impossible to see keys in low-light environments or when wearing HMD
- Work-arounds possible
- Positive:
  - Symbolic input in 3D less frequent than in 2D

Thad Starner

Symbolic Input: Keyboard Based Techniques

- Miniature keyboards
- Low key-count keyboards
  - e.g. mobile phone SMS; T9 system
- Chord keyboards (e.g. Twiddler)
  - Training required
- Pinch keyboard
  - Based on pinch glove
- Soft keyboards



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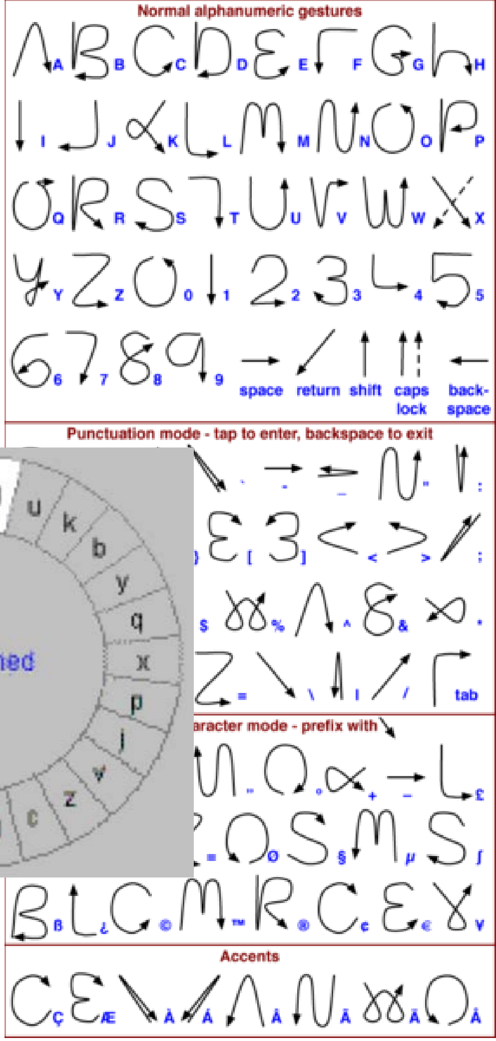
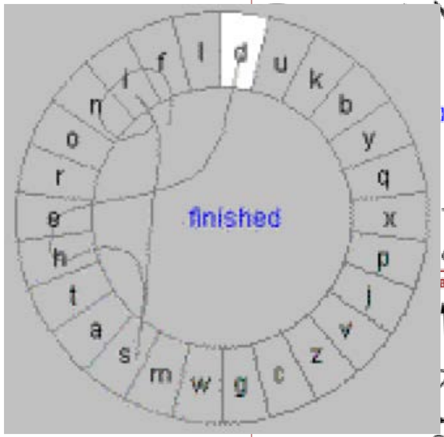
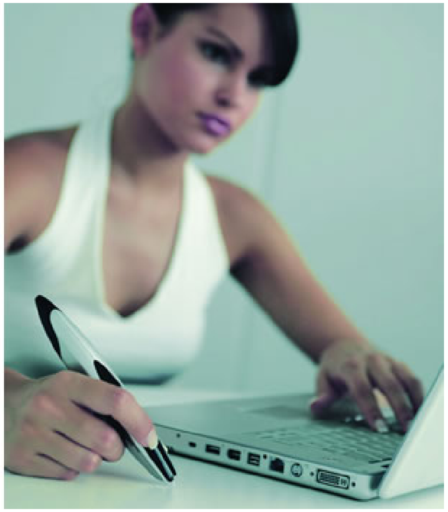
Pen Based

- Pen-Stroke Gesture Recognition
  - PDA Graffiti Alphabet
  - Cirrin soft keyboard
- Pen Input (Digital Ink)
  - Recognition of handwriting





scrivo.1



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Gesture-based Techniques

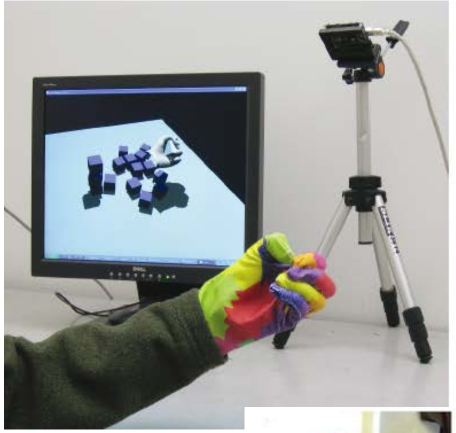
- Either by using gloves, computer vision or motion capture
  - Difficult: Fast Gesture recognition needed
  - Today more and more vision based approaches (with depth cameras)

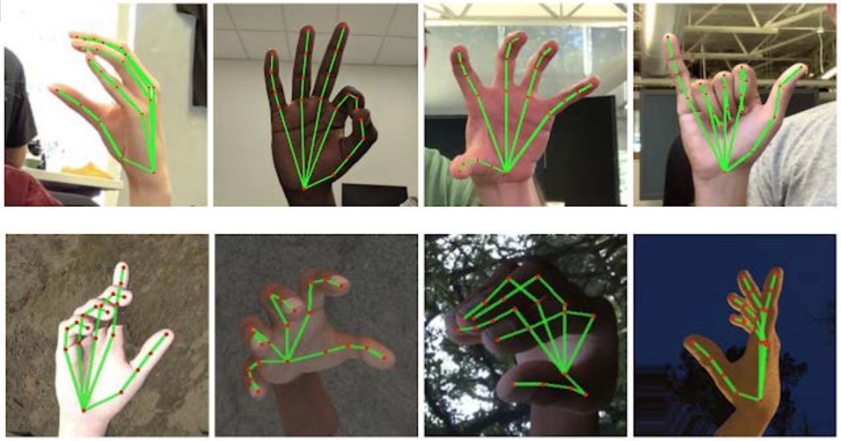
3 Types:

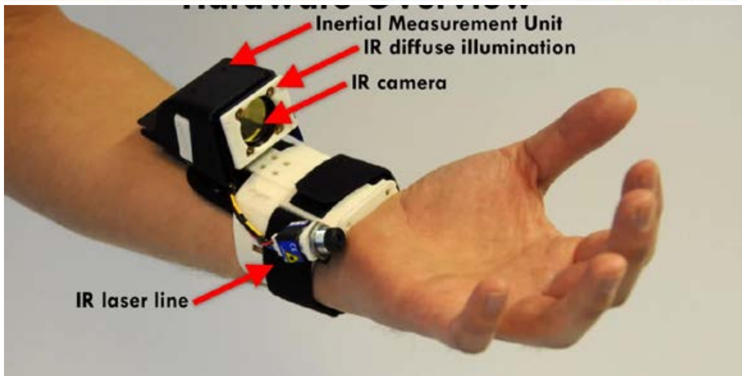
- Numeric gestures
  - Use of fingers represent number
    - Both hands can be used
  - No application of this technique known
- Sign language gestures (only small percentage of population knows sign language)
- Instantenous gestures

Sign Language Gestures

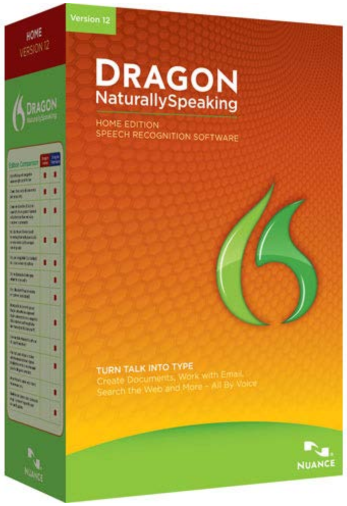
- Glove based
- 2D vision based
  - Difficult in real time
  - Occlusions
  - Using machine learning
- 3D Motion Capture solutions
  - Many approaches
  - See depth cameras & 3D User Interaction







Speech Input



- Complementary to other modes of interaction
- Got MUCH better due to machine learning approaches
- Issues to consider
  - continuous vs. one-time recognition
  - choice and placement of microphone
  - training vs. no training (= speaker independent)
  - handling of false positive recognition
  - surrounding noise interference
  - Language dependent

Speech Input - Hardware

- Headset:
  - wired or wireless (Bluetooth, RF)
  - surround sound (5.1, 7.1)
  - active noise cancelling

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Tracking

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Tracking systems

- Measure position and/or orientation of a sensor
  - 6 degrees of freedom in space
- Most VEs track the head and the hand
  - Correct viewing perspective
  - Interaction

Quality Factors & Criteria

- Degrees of freedom (3D pos.+orientation → 6DOF)
- Range or working volume
- Accuracy
  - Static
  - Dynamic
- Time for measurement - phase lag, “Real-time”
- Update rate (measures/sec)
- Signal to noise ratio
- Registration
- Sociability (Tracking should not hinder freedom)

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Range, Working Volume

- Amount of space, where tracker works
- Range:
  - Distance from sensors
  - FOV of camera
- Working volume:
  - Volume resulting from ranges
- Time until stability degenerates
  - E.g. Drifting of inertial trackers

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Static & Dynamic Accuracy

Static Accuracy: Maximum deviation from fixed tracker position to fixed reference value

- Influenced by:
  - Receiver sensitivity, Transmitter s/n ratio, A/D converter resolution, (Analog component noise tolerance levels), Environmental effects, Algorithmic errors, Installation errors

Dynamic Accuracy: Accuracy as sensor is moved

- Dependent on static accuracy
- Influenced by:
  - Processor type, System architecture, Time dependent system components

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Tracking System: Generic Architecture (Latency, Lag, Update Rate)

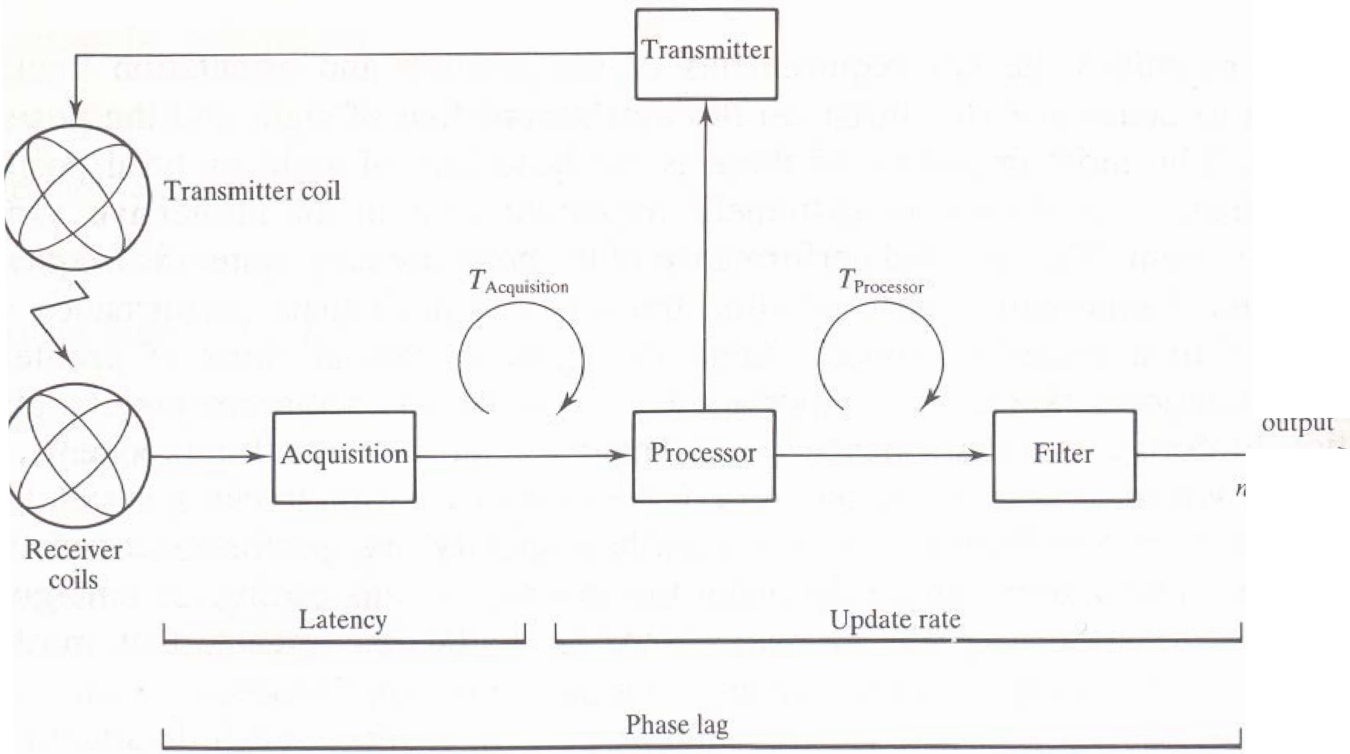

Figure 6.11 Generic architecture for a head tracker system.

Latency & Update Rate

Latency: Rate at which acquisition portion of system can acquire new data

- Aspects:
  - Hardware limitations
  - Time to sense change in receiver's position
- Example - optical tracking: Time to capture image

Update Rate: Trackers ability to output position and orientation data

- Influenced by:
  - System processor
  - Algorithm
- Example: Time to process image & extract data

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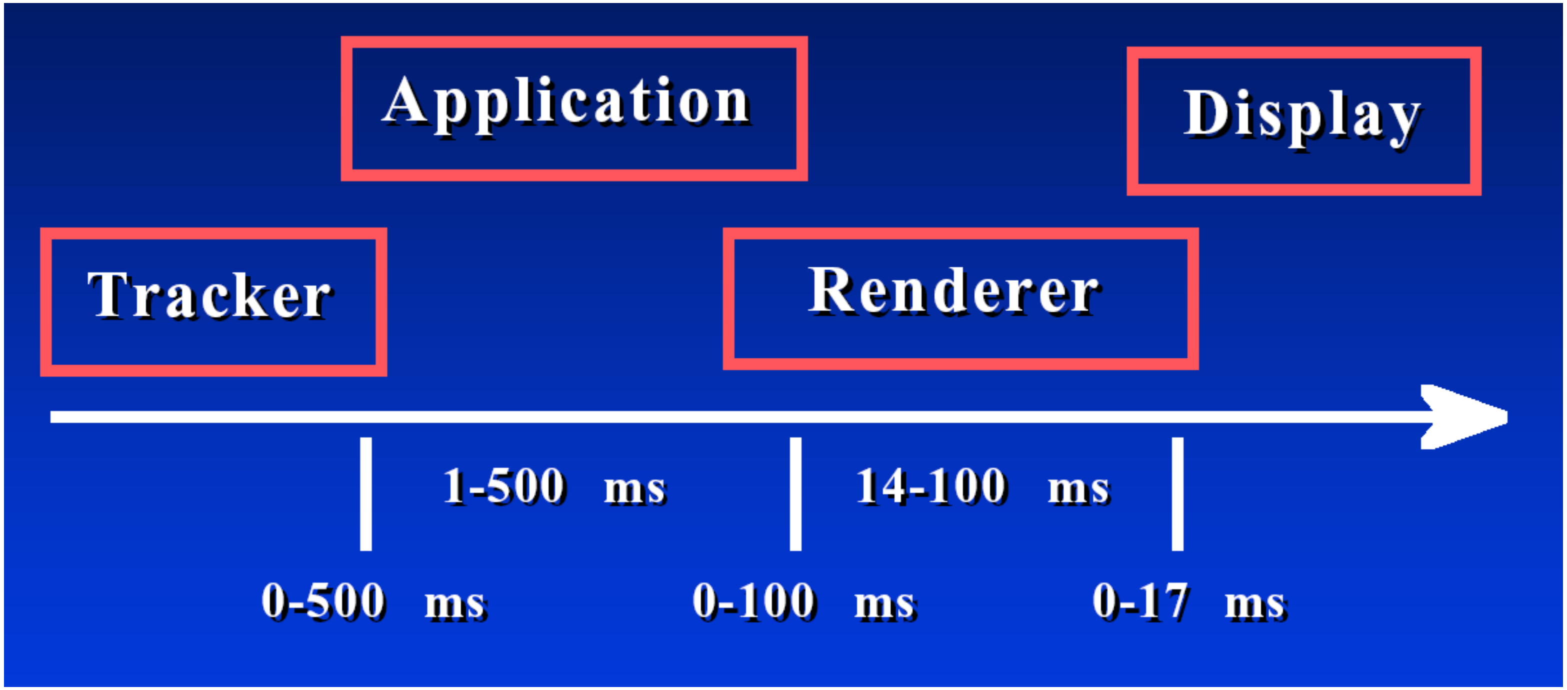
Phase Lag

- Latency + update rate
- Fast motions - tracker cannot keep track
- Contributors:
  - Architecture
  - Processor type
  - Algorithm
- Improving one of these can reduce lag

Visually coupled System – Still Interactive?



Tracker: phase lag
Application: time to process tracking data
Time for rendering
Interactivity: 15-20 FPS; Recommendation: 90 FPS

Low Latency – State of the Art

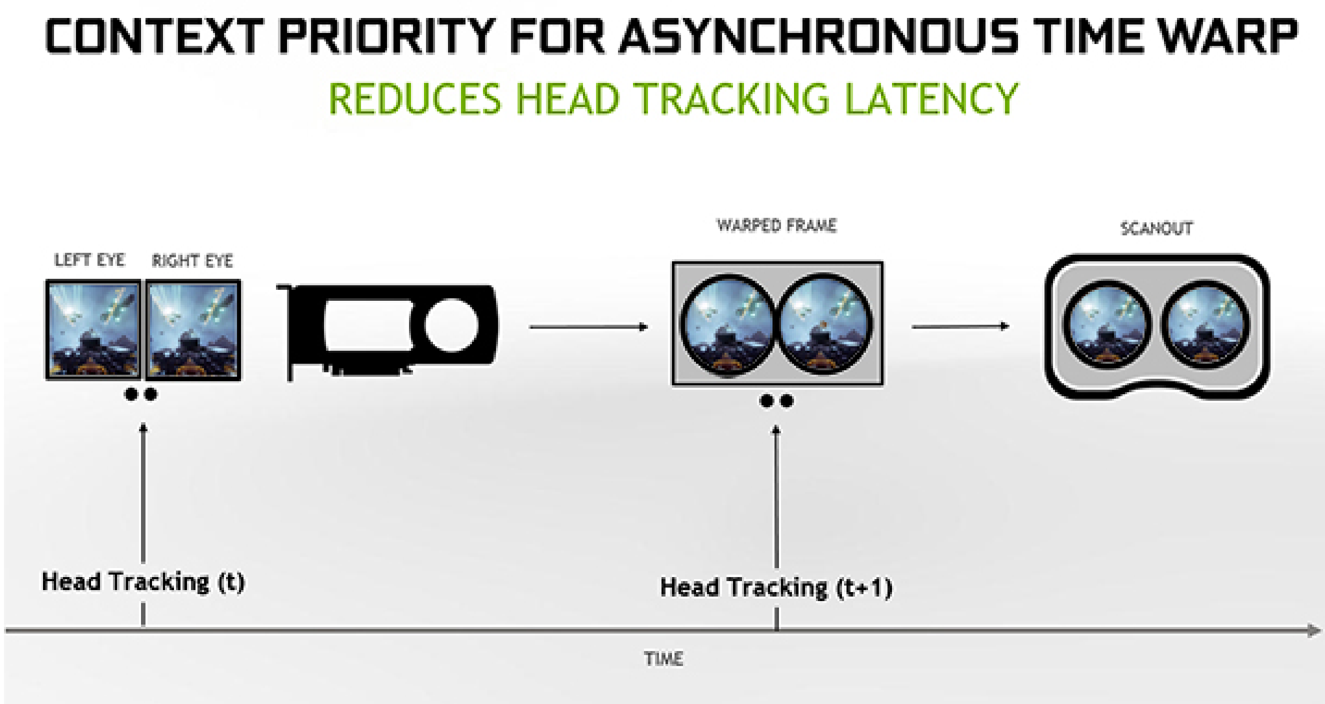
- On low latency in VR – see Michael Abrash‘s (Oculus VR) talk about

What VR Could, Should, and Almost Certainly Will Be within Two Years

http://youtu.be/G-2dQoeqVVo

(Feb. 11, 2014)

Asynchronous Time Warp



- Front Buffer Rendering
- Single Pass Stereo

Still 7ms difference between left/right eye on single display HMDs -> 2 displays used

Registration (esp. for AR)

- Correspondence:
  - Actual position / orientation = Reported position / orientation
- Good accuracy/resolution - does not imply good registration
- Important for more than one sensor
- Important usabilty factor – can cause bad side effects (Cybersickness)

Effects of Inaccurate Tracking

- Objects appear where they are not
- Proprioceptive conflicts
  - Static: limb location conflicts
  - Dynamic: visual delay (lag)
  - Limb jitter or oscillation
- Misregistration
  - Constant OK (immersive, non see-through)
  - Changing can hurt
- User forced to adapt
- Simulator sickness (Cybersickness)

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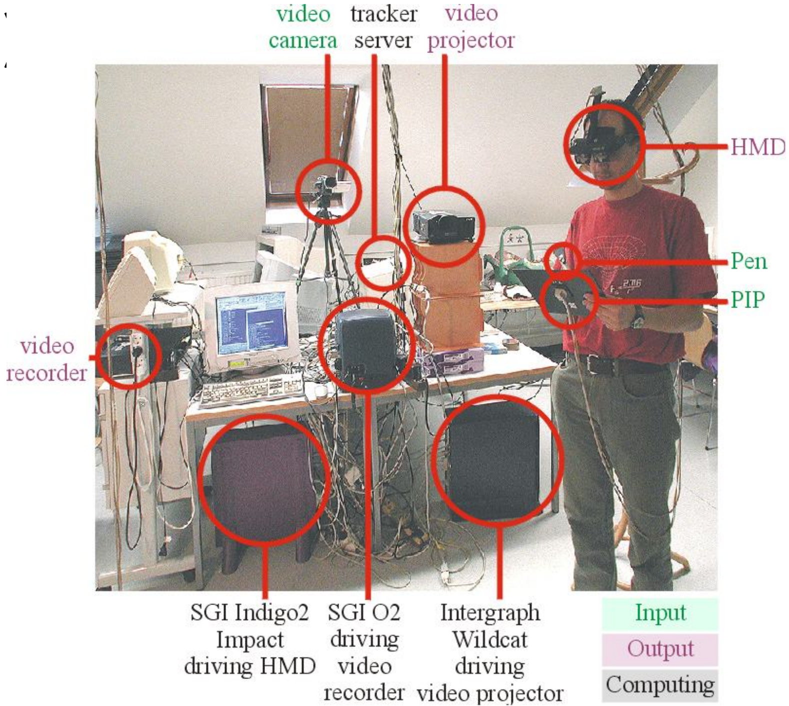
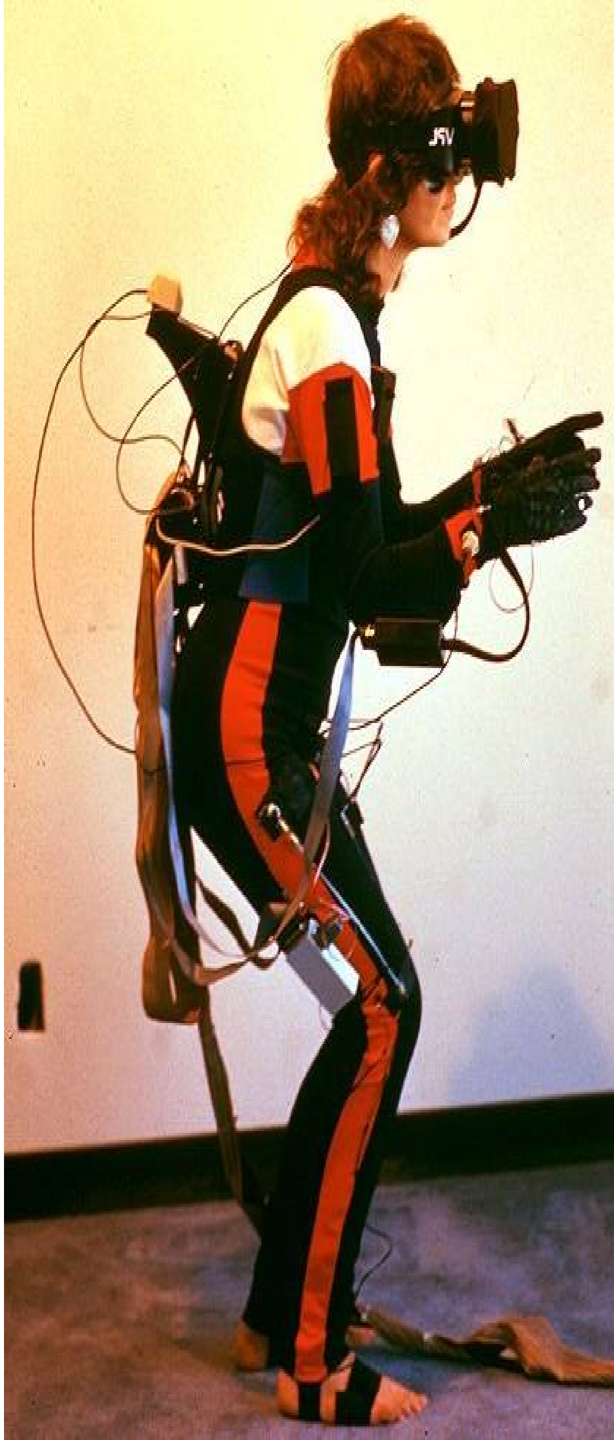
Sociability

- Can it be used by multiple users?
- Is interaction possible then?
- Restrictions by:
  - Operating principle (number of sensors, occlusions)
  - Weight
  - Size
  - Phase lag
  - Wires
  - ...





Classification by Operation Principle

- Mechanial
- Magnetic (AC/DC/passive)
- Optical
  - Marker based
  - Natural feature; Vision (Gestures)
  - Motion capture
- Inertial (gravity, acceleration)
- Time-of-Flight & Frequency Measuring
  - (Radio Waves) GPS ...
  - (Sound waves) Acoustic
- Hybrids (combination of multiple)

Structure – Tracking Hardware

- Technological Principle
- Technological Advantages & Disadvantages
- Human Factors Advantages & Disadvantages
- Examples

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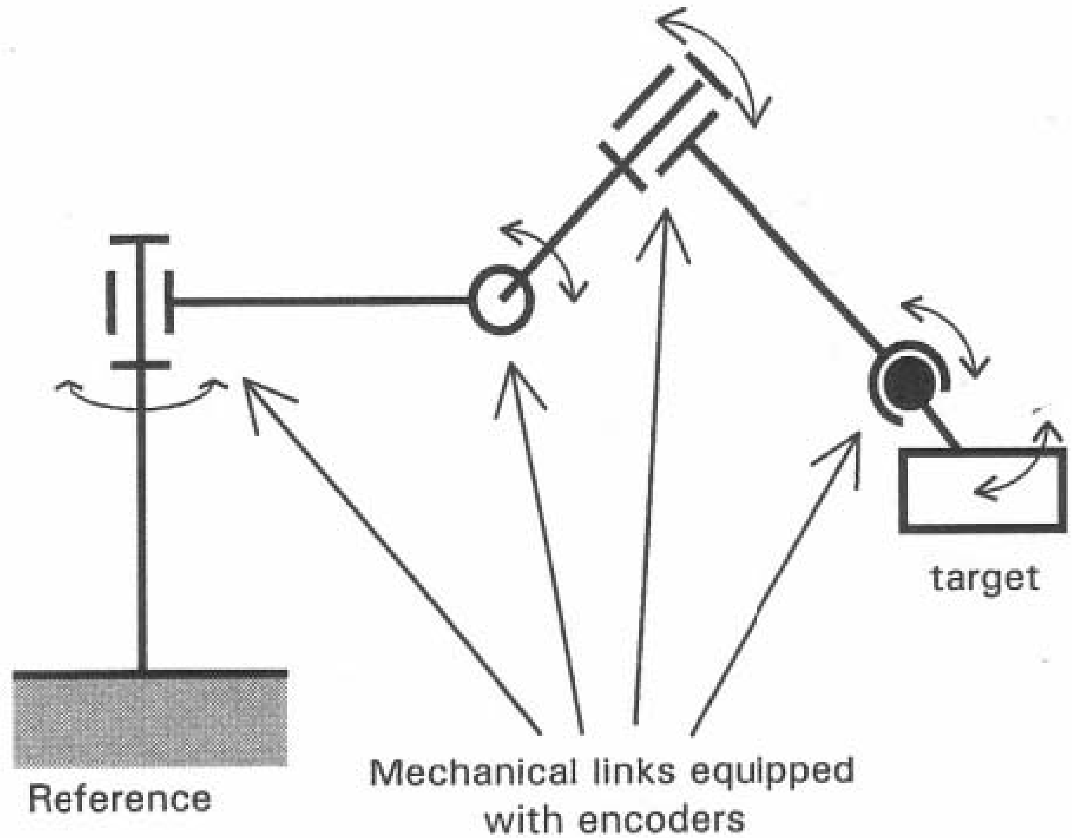
Mechanical Tracking



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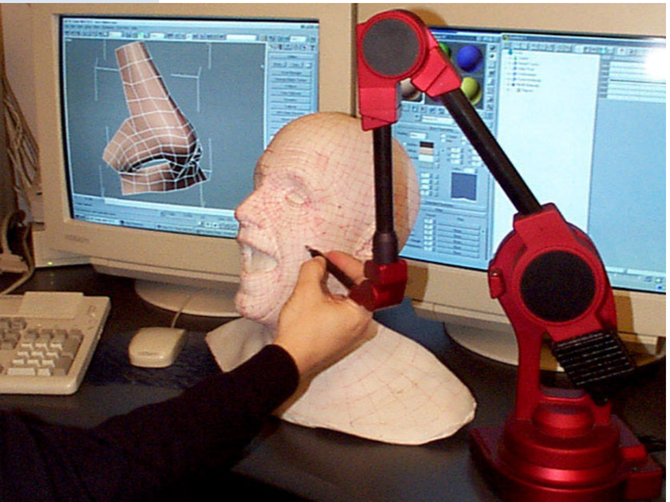
Mechanical Tracking

- Oldest tracking technology
- Measure angle of human joints
- Potentiometers for angular measurements
- Position reconstructed using kinematics



Mechanical Tracking

- Advantages
  - Technology well known
  - Tracks multiple users in real-time
- Disadvantages
  - Ground-referenced
    - Limited working volume
  - Uncomfortable
  - Exoskeleton
    - affects movement
    - Need to adjust per person, can be ill-fitting
    - No global movement tracking

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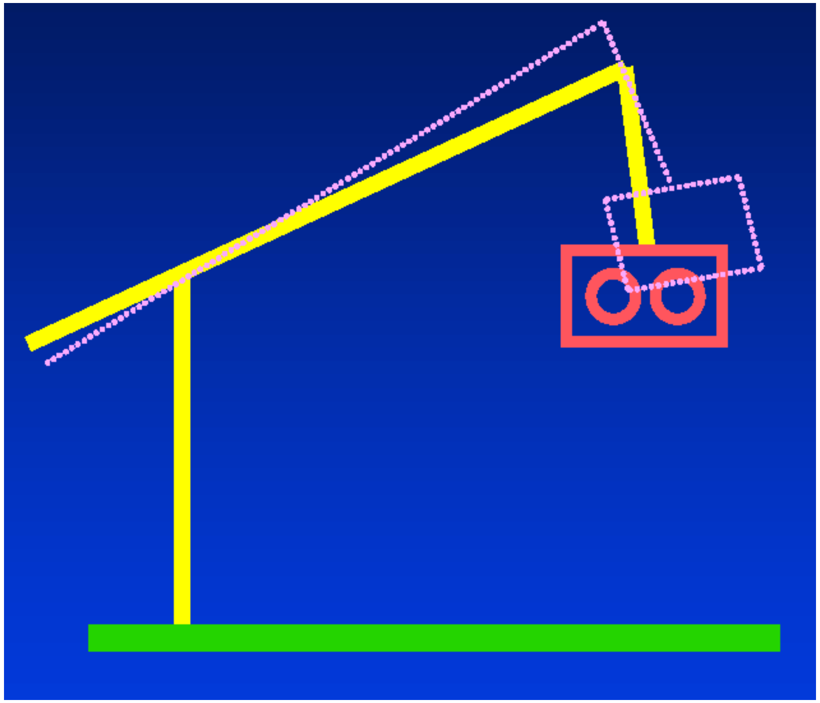
Mechanical

- Pros
  - High precision
  - Very fast
  - High S/N
- Cons
  - Infrastructure
  - Compounded measurement error
  - Restricted working volume
  - Restricted motion
  - Not very sociable



Fakespace

Boom
3C/HF/Push

Shooting Star
Technologies

ADL-1

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CyberForce

- Most natural interface - the human hand
- Immersion Corp. Products:
  - CyberGlove
  - CyberTouch
  - CyberGrasp
  - CyberForce
- 6DOF tracking
- Usability problem

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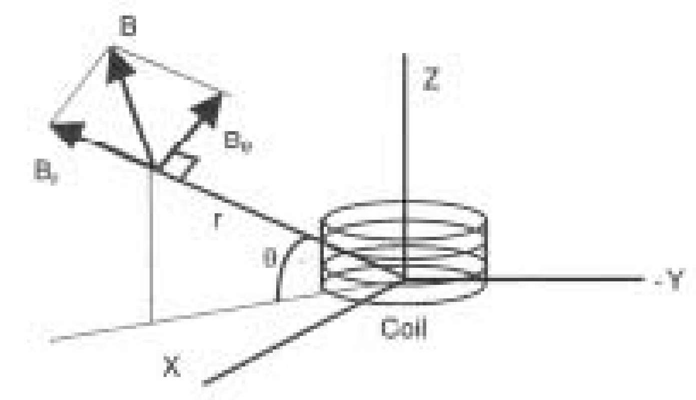
Magnetic Tracking

- Circulating electric current in coil -> magnetic field is generated
- At distance r, the field has polar coordinates B_0 and B_r



- Magnetic flux is created in reciever (magnetic field sensor)
- Magnetic flux: Function of distance and orientation relative to coil
- To measure position and orientation of reciever in space, emitters consist of 3 orthogonal coils and recievers of 3 sensors -> combination of three elementary orthogonal directions

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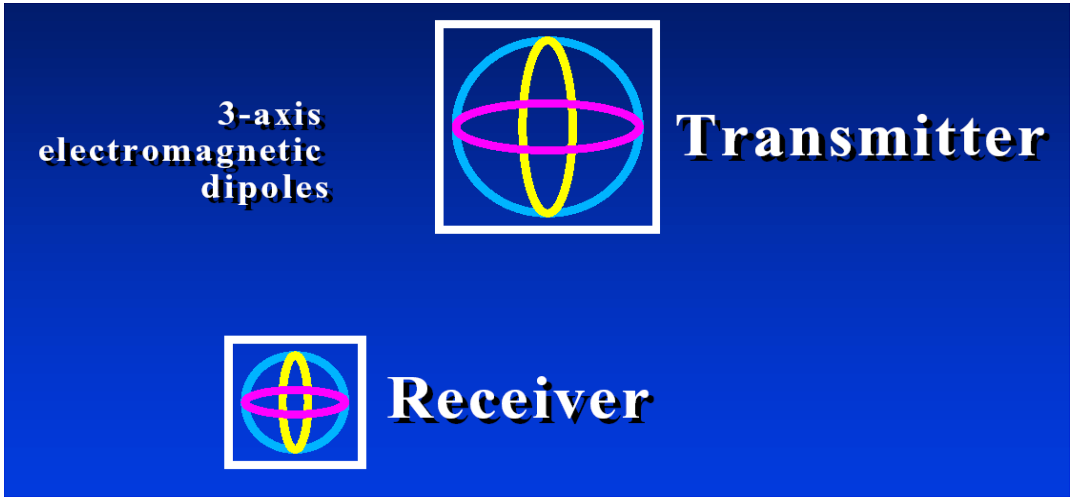
Magnetic Tracking - Alternating Current (AC)



- Transmitter: electromagenetic dipoles -> AC field
- Receiver: induced voltage measured
- Voltage dependent on:
  - Distance transmitter <-> receiver --> position
  - Orientation of coils in magnetic fields --> orientation

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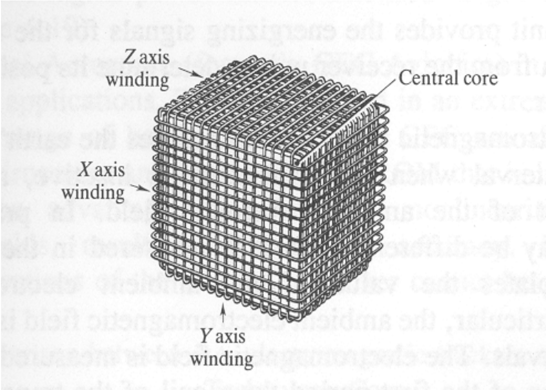
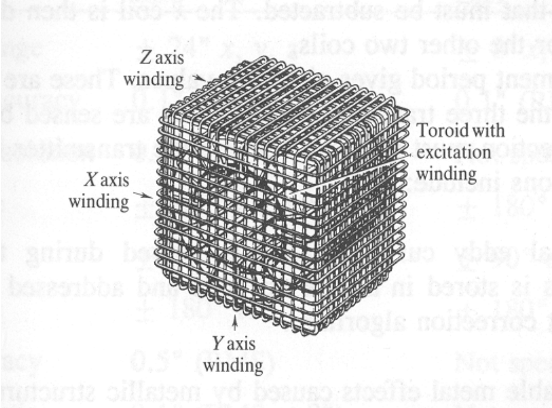
DC Magnetic - Overview

- Similar operation to AC
- Short DC pulses vs. contin. AC
- Transmitter
  - 3 orthogonal coils, cubic core
  - Mounted rigidly to reference structure
  - Driven sequentially
- Receiver
  - 3 orthogonal coils, cubic core
  - Additional energizing coil
  - All 3 measures concurrent
- 4 phase measurement (4.: earth magn. Field – subtract out)

Transmitter



Receiver



Magnetic: Advantages

- No line of sight restrictions – continuous data
- Small/lightweight sensors
- Wireless versions available
- Off the shelf available, robust
- High update rate (200 Hz or more)
- Price depends on tracking range – can be relatively inexpensive

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Magnetic: Disadvantages

- External noise
  - At metal, power wires,…
  - Unwanted eddy currents (Field distortions)
    - conductive material will distort the magnetic field (monitors)

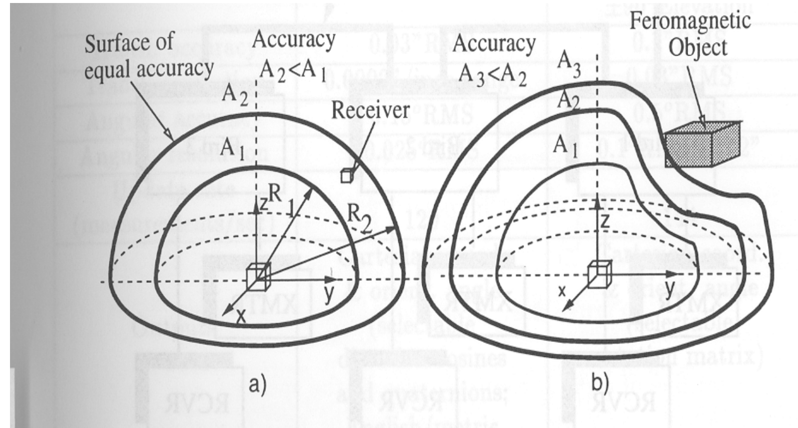

Figure 2.7: *3-D Magnetic sensor accuracy degradation: a) with distance; b) due to metallic objects [Burdea, 1993-b].*

- Field strength ~ 1/d^3
  - Jitter at boundaries (Filtering increases phase lag)
  - Cannot increase electromagnetic field strength -> might have consequences on humans
- Not the best accuracy
- Limited working volume (max. 3-5m radius)

AC Magnetic Products

- Polhemus (Fasttrak, InsideTrak, LongRanger ...)

Longranger:
sphere ~ 50 cm
with orthogonal coils

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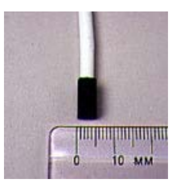
DC Magnetic - Ascension

[Video of our former VR lab]

Flock of birds

MotionStar



MiniBird

PciBird

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AC/DC Magnetic - Specifications

AC

Model	Latency	Max. # of sensor	Range	Accuracy	Costs
FastTrak	4 ms	4	~ 3 m	2mm, 0,15 degree	€ 7.000
IsoTrak	20 ms	2	~ 1,5 m	0,25 cm; 0,75 degree	€ 3.500
LongRanger		4	~ 10 m		
InsideTrak	12 ms	2	~ 1,5 m	1,25 cm; 2 degrees	€ 1.200
UltraTrak Pro	6 ms	32	4,5 m	2,5 – 7,5 cm, 3 deg.	€ 75.000

DC

Model	Latency	Max. # of sensor	Range	Accuracy	Costs
Flock	20 ms	30	~ 1 m	0,25 cm; 0,5 degree	€ 3.000
Flock 10	20 ms	30	~ 3 m	3 cm; 1 degree	€ 8.000
MotionStar	20 ms	120	~ 3 m	3 cm; 1 degree	€ 33.000
MotionStar Wireless	20 ms	18	~ 3 m	3 cm; 3 degree	€ 64.000

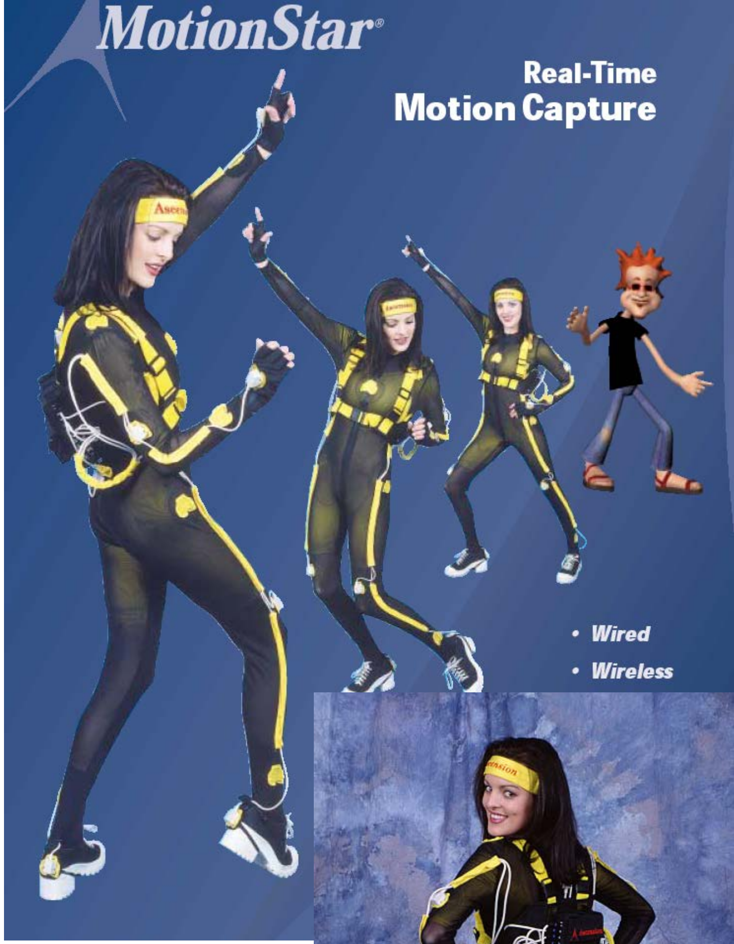
All latency times without filtering

Magnetic: MotionStar

- Wireless Magnetic Tracking System
- Up to 20 sensors

→ Motion Capturing

- More than one transmitter possible



Sensors: 20/suit

100 updates/sec
3 meters range
from base unit
Resolution<2 mm
and <.2 degrees

Electronic unit
(2 hours battery life)

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Razer Hydra & Sixense STEM System

- Low cost PC controller
- 6 DOF AC magnetic tracking
  - Very low field strength (1/40 earth magn. field)
  - Switching polarity with ~8,000 Hz
- 1 mm, 1 deg accuracy
- Hydra: Range ~1.5 m from base
- Low latency, no line of sight
- Distortions from metallic objects
- Sixense STEM System
  - Wireless, longer range (3.5m), 5 sensors…
  - Additional inertial sensor as distortion compensation!

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Passive Magnetic

- Devices
  - Compass (magnetometer)
- Measure
  - Earth's magnetic field
  - Heading only (2DOF)
- Pros:
  - No infrastructure, Available outdoors, Absolute reference
- Cons
  - Affected by
    - Other ferrous and magnetic materials
    - Active magnetic sources
  - Limited information (2D orientation only)
  - Field is very tilted in significant parts of the world

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Optical Tracking

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Optical Flow
Motion Estimation

- Easy to implement
- Watch pixel movement
- Compare movement vectors of pixels
- Indicates movement direction
- Not very accurate!

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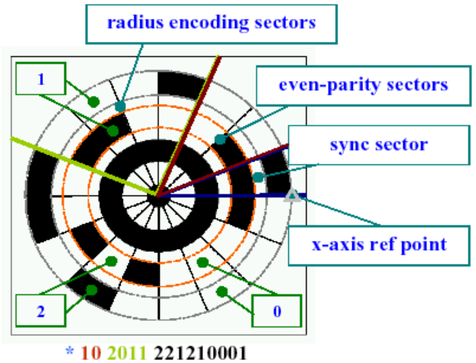
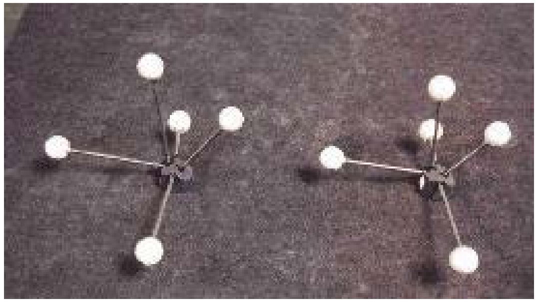
Vision Trackers

Types

- Fiducials
  - ARToolkit
    - Video1: Magic Book
    - Video2: Cockpit Layout
    - Video3: Invisible Train
  - ARTag
  - Intersense
- Markers/LEDs
  - Active / Passive
- Natural features
  - Images
    - Video: IKEA Katalog
  - 3D objects
  - Various research projects





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Vision-based Tracking

- Most devices have cameras

- Marker-based
  - Artoolkit port

- Natural Features
  - SIFT, Surf, FERNs
  - Active search tracking

- Recognition, Initialization, Mapping and Tracking

Marker Tracking

- Has been done for more than 15 years
  - Mobile phones today are faster than computers of that time
- Several open source solutions exist
- Fairly simple to implement
  - Standard computer vision methods
- A rectangular marker provides 4 corner points

-> enough for pose estimation!

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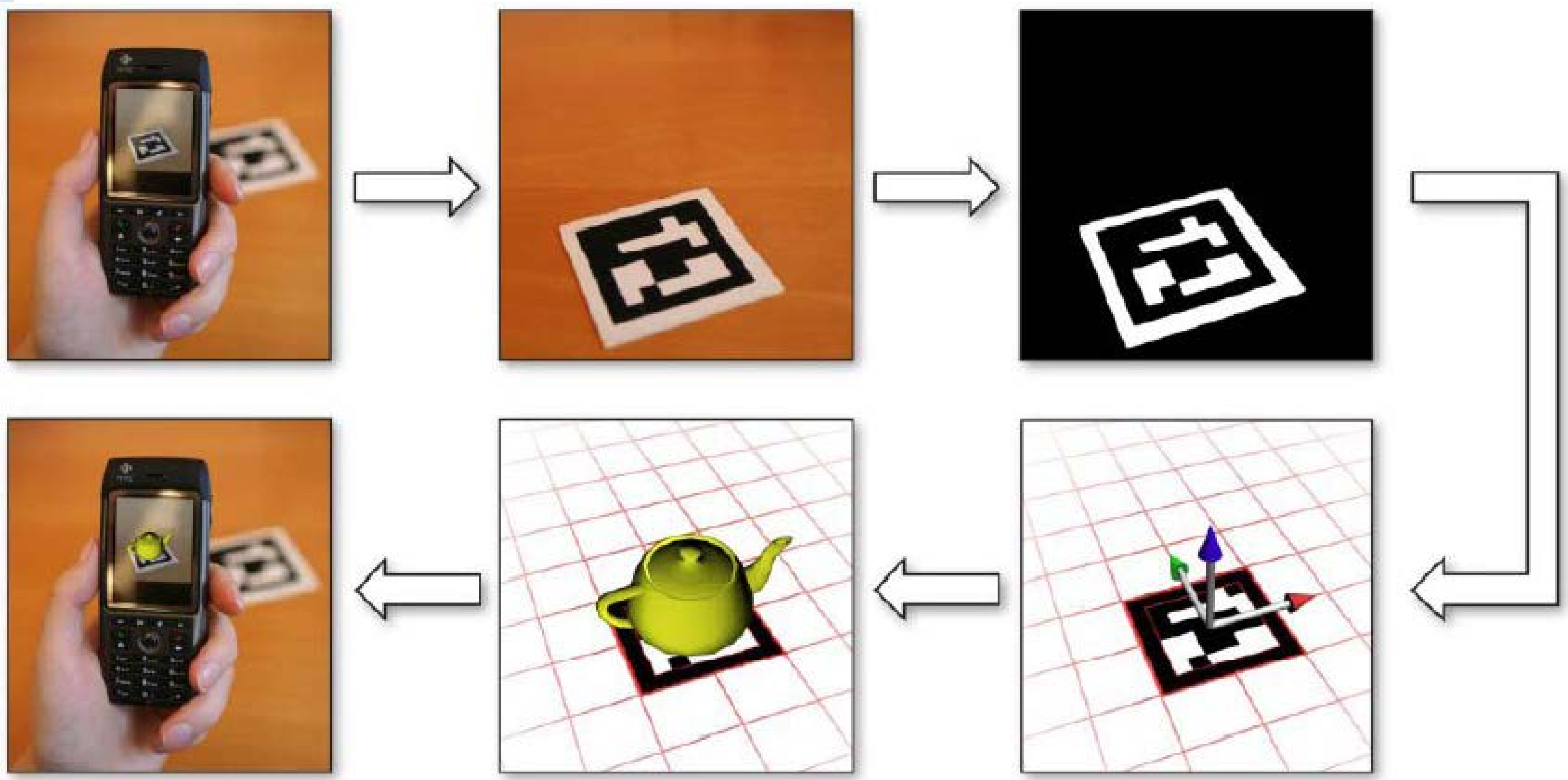
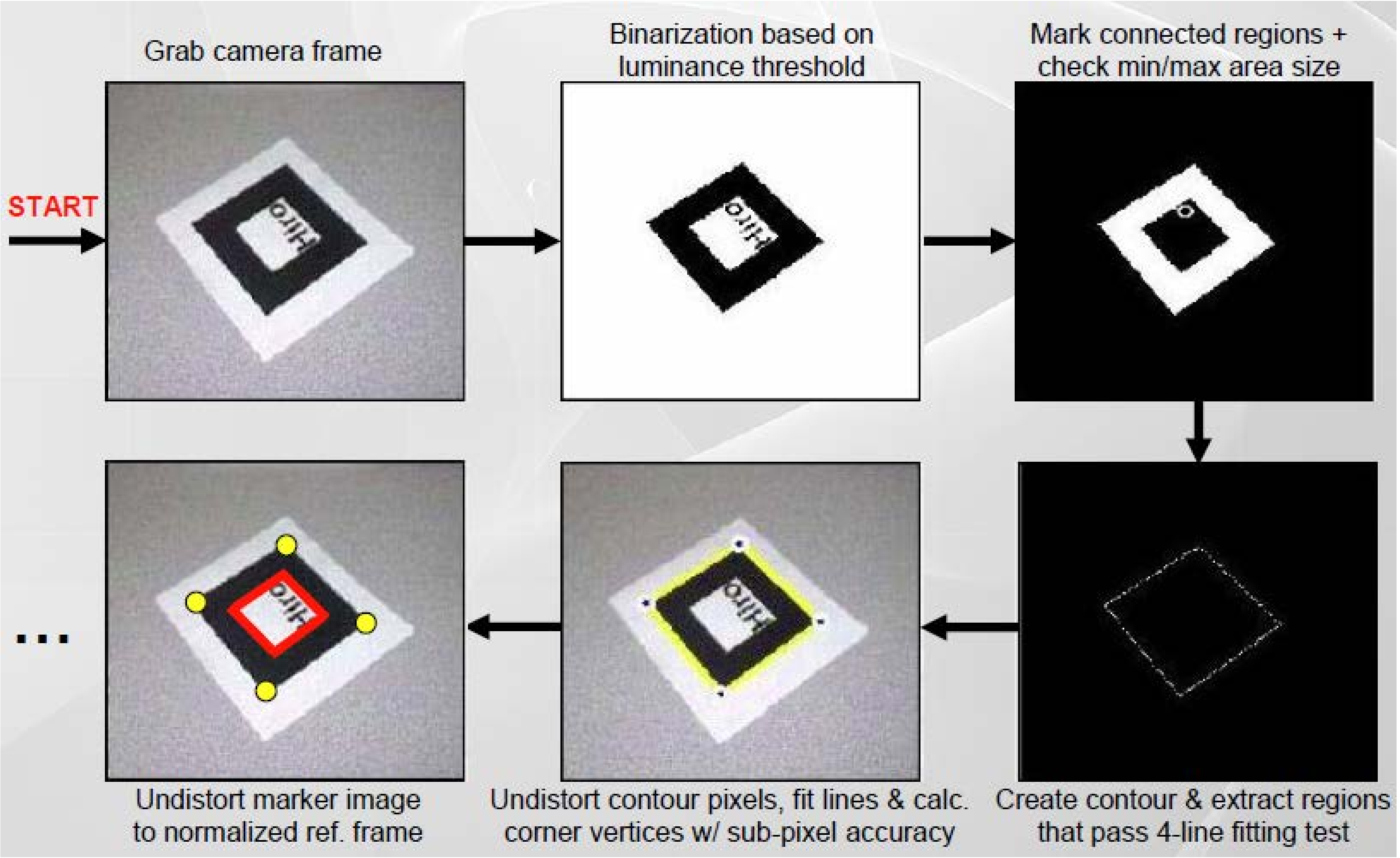
Marker Tracking: Pipeline Overview



Goal: Do all this in less than 20 milliseconds on a mobile phone

Marker Tracking: Overview 1/2



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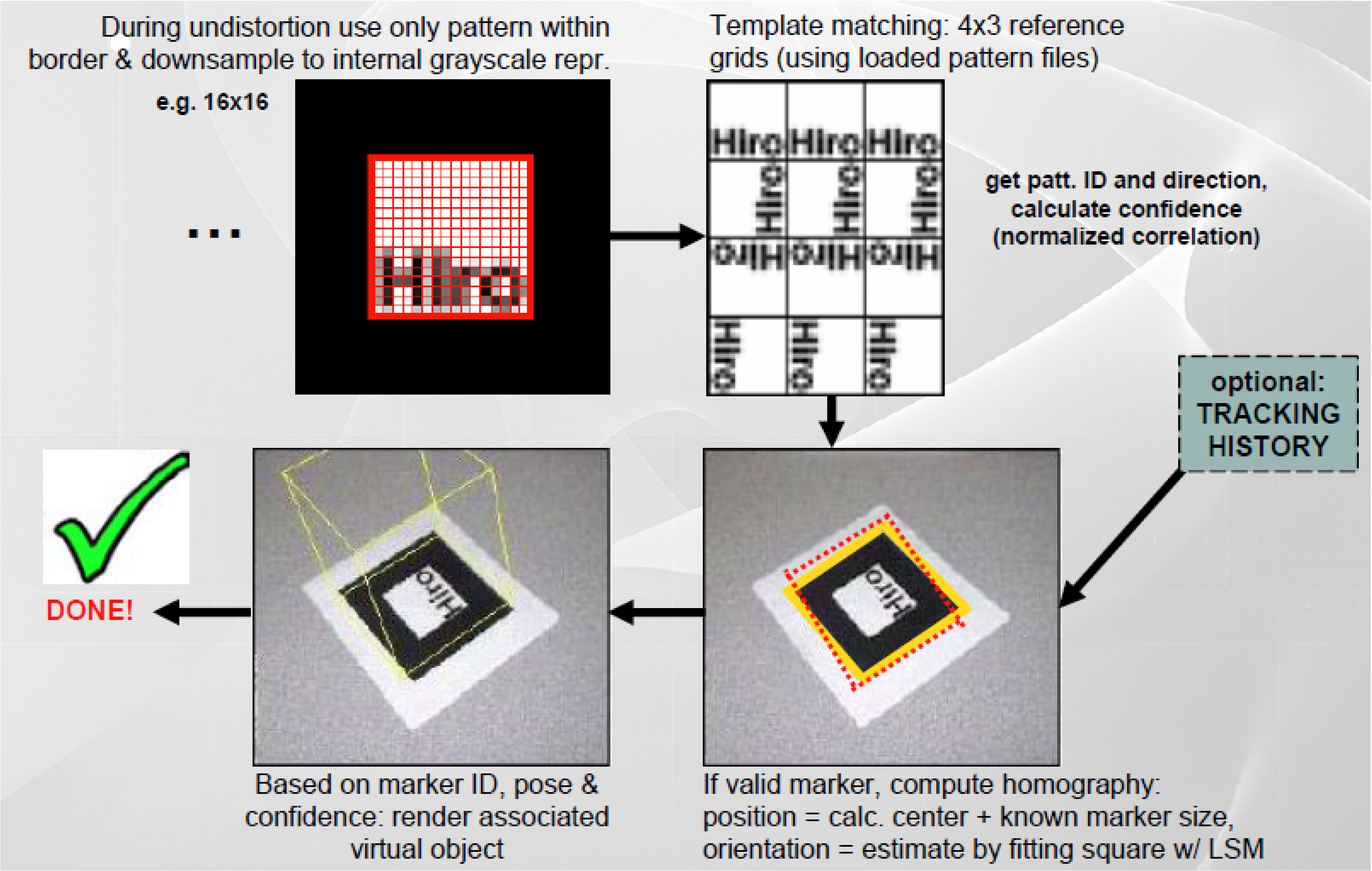
Marker Tracking: Overview 2/2



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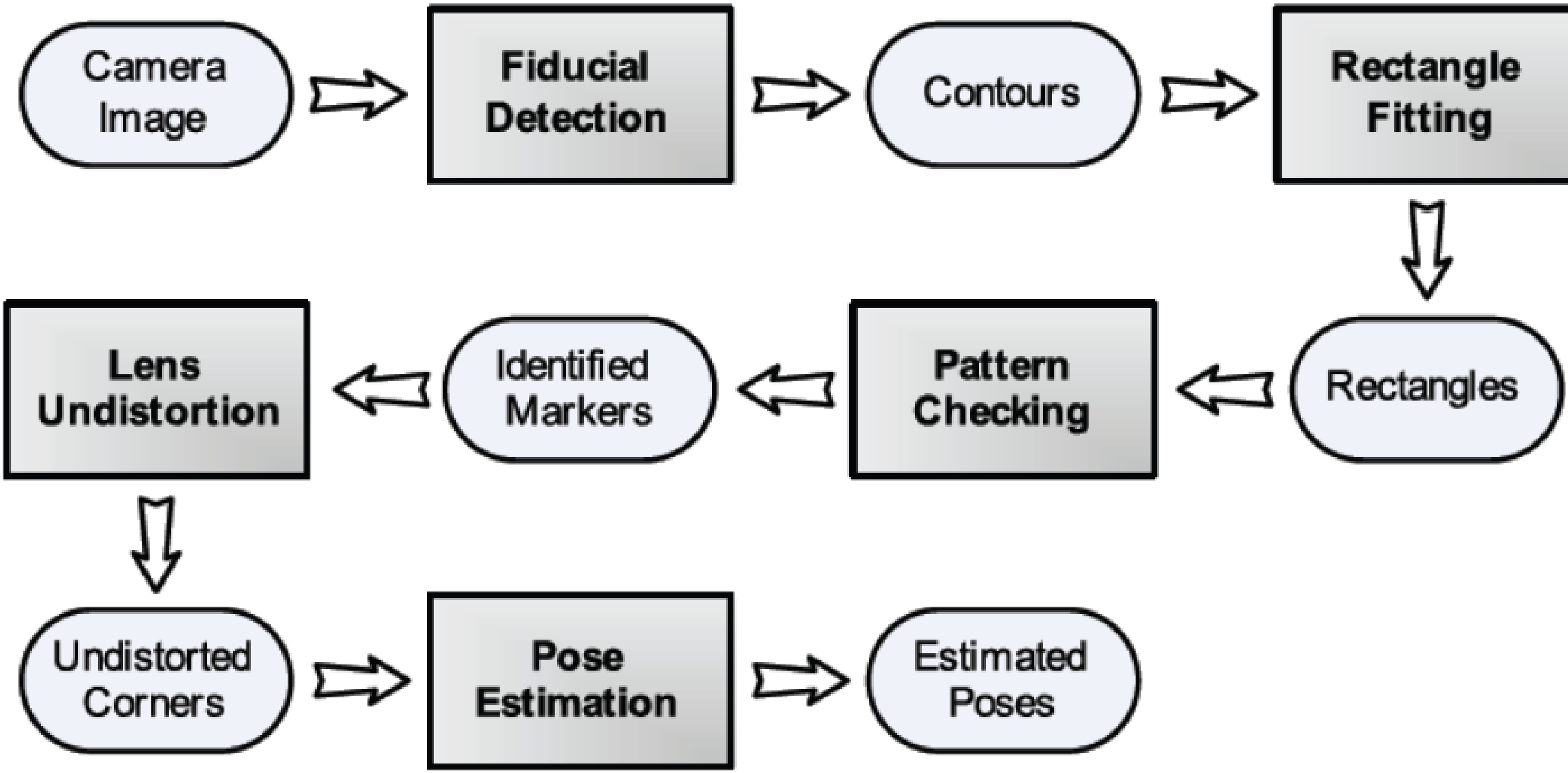
Marker Tracking: Overview Pipeline



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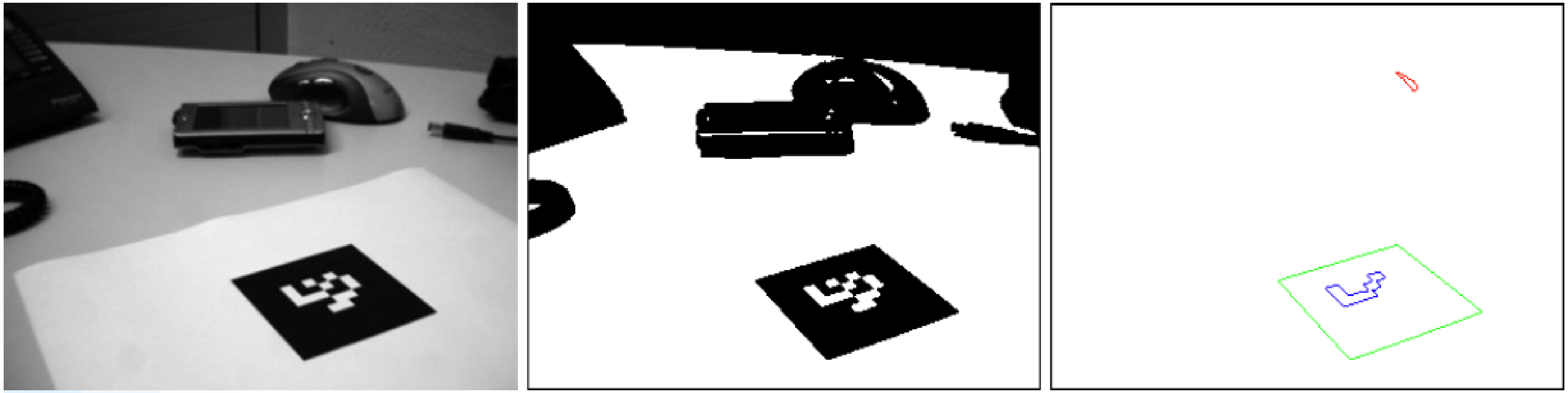
Marker Tracking: Fiducial Detection

- Threshold the whole image
- Search scan-line per scan-line for edges (white to black steps)
- Follow edge until either
  - Back to starting pixel
  - Image border
- Check for size
  - Reject fiducials early that are too small



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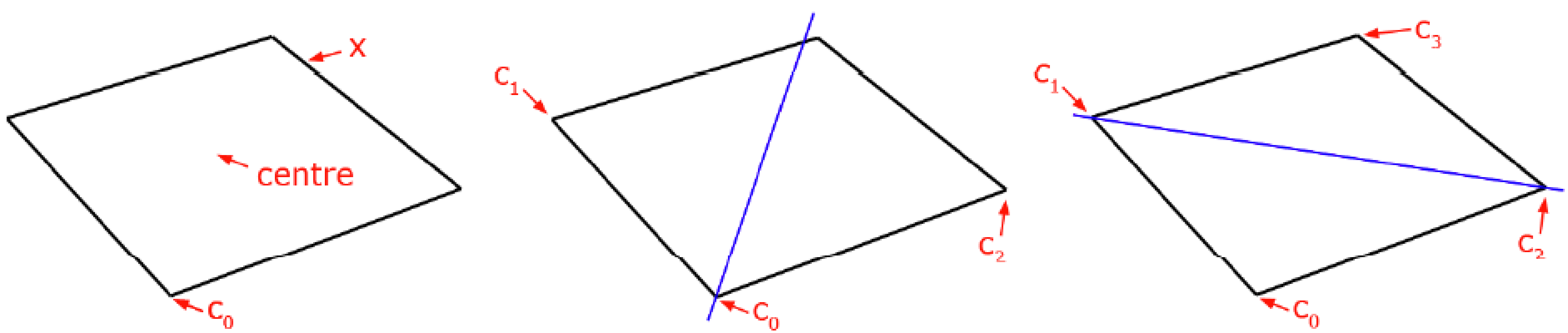
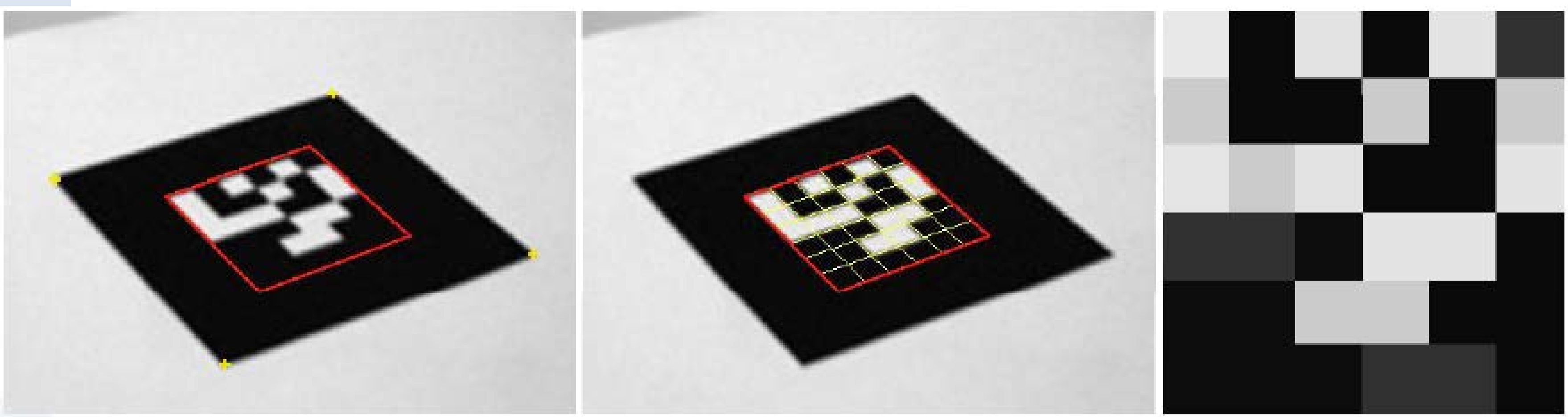
Marker Tracking: Rectangle Fitting

- Start with an arbitrary point "x"
- The point with maximum distance must be a corner c0
- Create a diagonal through the center
- Find points c1 & c2 with maximum distance left and right of diagonal
- New diagonal from c1 to c2
- Find point c3 right of diagonal with maximum distance
- Repeat to check if no more corners exist



Marker Tracking: Pattern checking

- Calculate homography using the 4 corner points
  - "Direct Linear Transform" algorithm
  - Maps normalized coordinates to marker coordinates (simple perspective projection, no camera model)
- Extract pattern by sampling
- Check pattern
  - Id (implicit encoding)
  - Template (normalized cross correlation)
- Four 2D-3D correspondences - pose estimation



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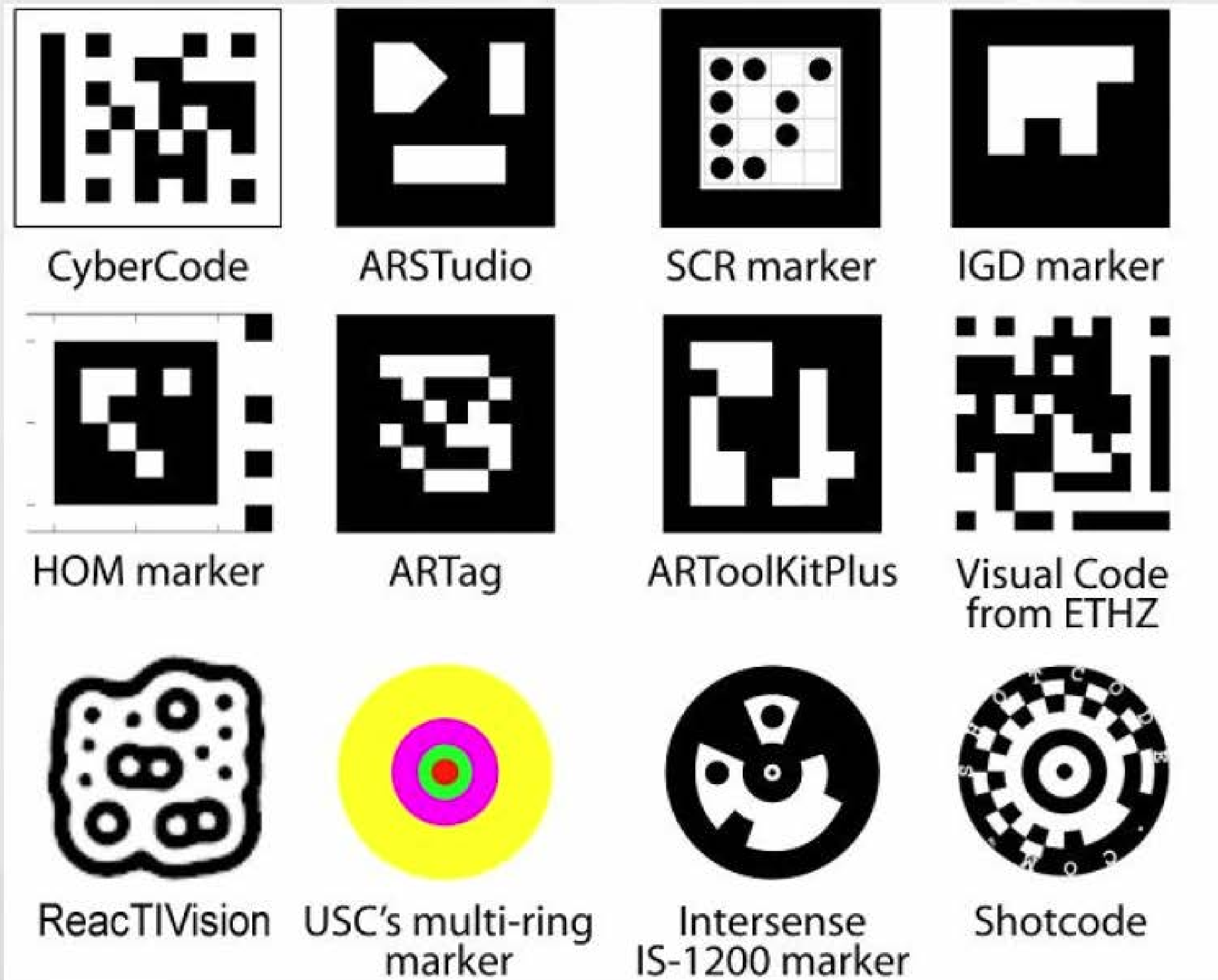
Other Popular Fiducial Marker Libraries for AR

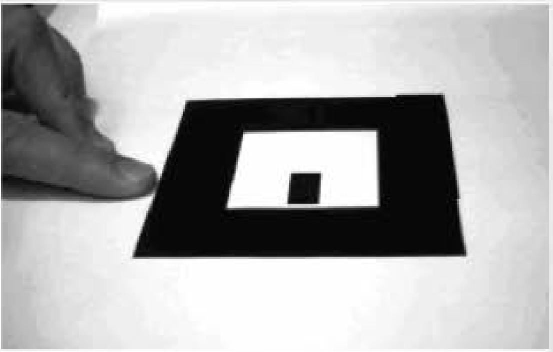


Improvements / diffs:

- Improved robustness (e.g. partial occlusion, error detection in pattern)
- Speed-ups and code optimizations
- Commercial libraries

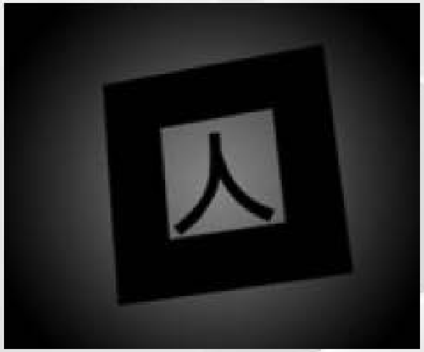
Non-exhaustive list

Tracking Challenges in ARToolKit



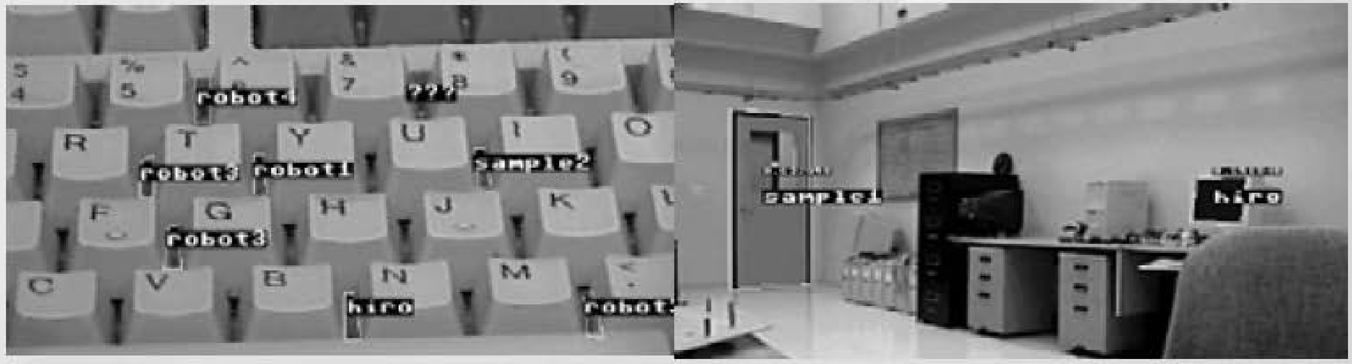
Occlusion
(image by M. Fiala)

Unfocused camera, motion blur



Dark/unevenly lit scene, vignetting

Jittering
(Photoshop illustration)



False positives and inter-marker confusion
(image by M. Fiala)

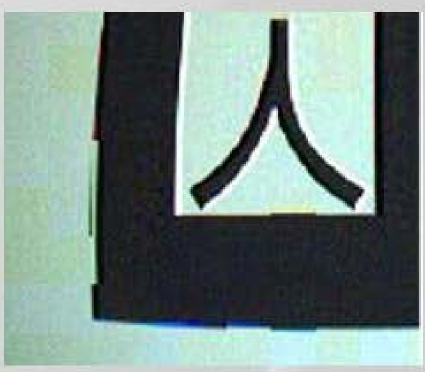


Image noise
(e.g. poor lens, block coding / compression, neon tube)

Fiducials - Sources of Errors

- „Optical noise“ – low resolution/pixel flickering
- Too far: Marker too small; too close: marker does not fit into image
- Ambiguity during detection
- Changing lighting conditions

Solution: Infrared light

- No problems in dark environments
- Active Markers: Emit light (e.g. IR LEDs)
- Passive Markers: Reflect light

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Inside-Out / Outside-In Tracking

- Outside-In:
  - Sensors (Cameras) are located at fixed reference point
- Inside-Out:
  - Sensors are located on mobile target
  - Higher resolution and accuracy in orientation than outside-in
    - Reason: produces larger motion in image -> larger displacement of pixels -> higher accuracy

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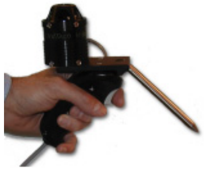
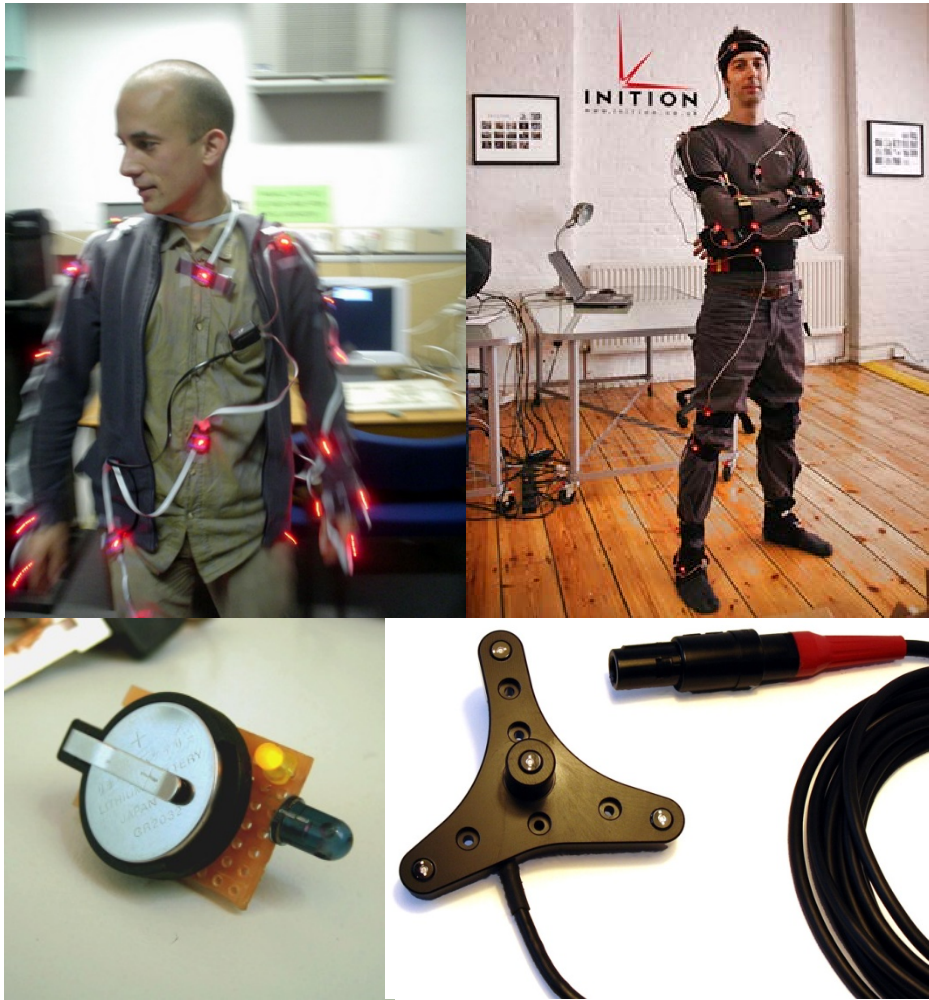
Inside-Out: HiBall

- HiBall-3100 wide area tracker
- HiBall: 6 lenses and photodiodes
- Active markers (IR LEDs)
- 6-DOF
- Hundreds of LEDs mounted on ceiling
- Very high accuracy
- High update rate: 2000 Hz



Overview: Tracking Active Markers

- Frequency-encoded IDs solve correspondence problem, but require high-speed cameras.
- Tethered or battery-powered markers restrict user movement.
- Higher cost of equipment, additional maintenance overhead.



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Optical Tracking - Polaris

- Optical
- Passive and active targets

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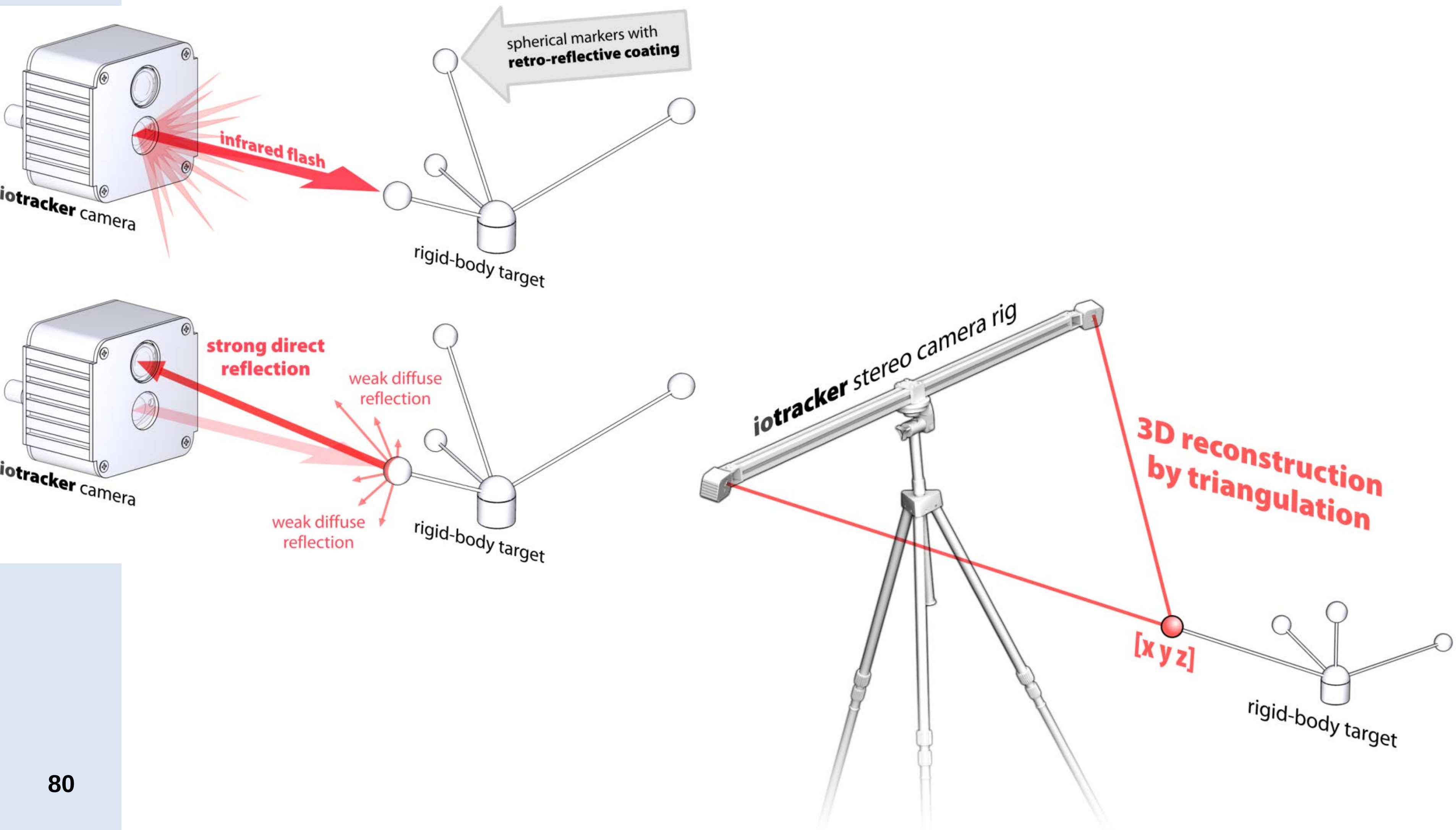
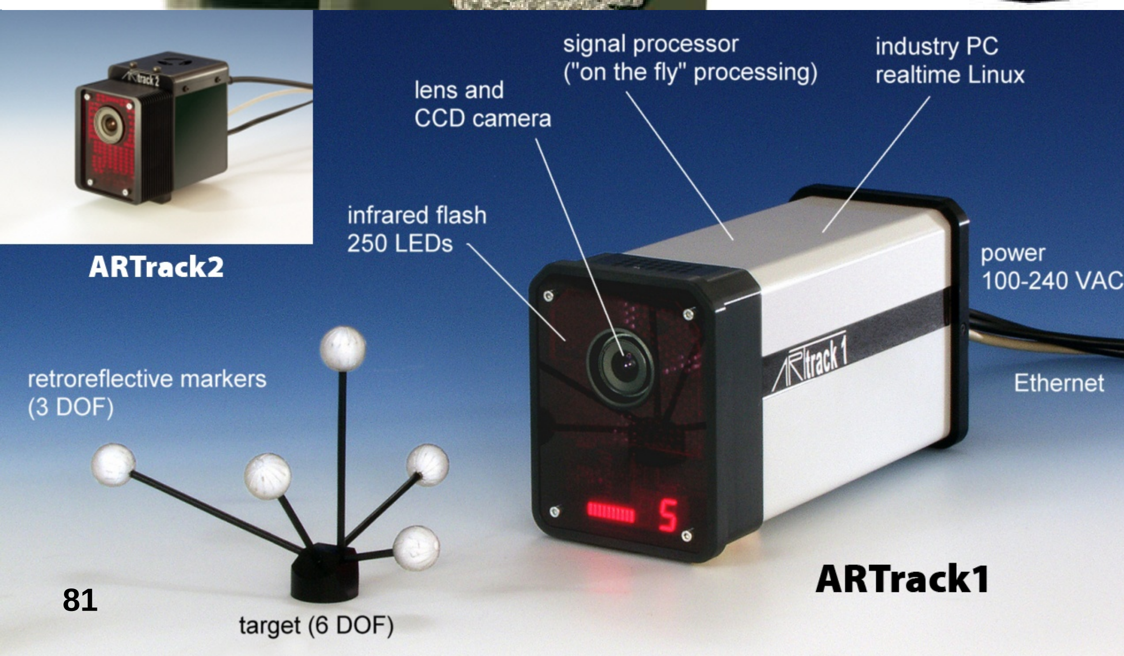
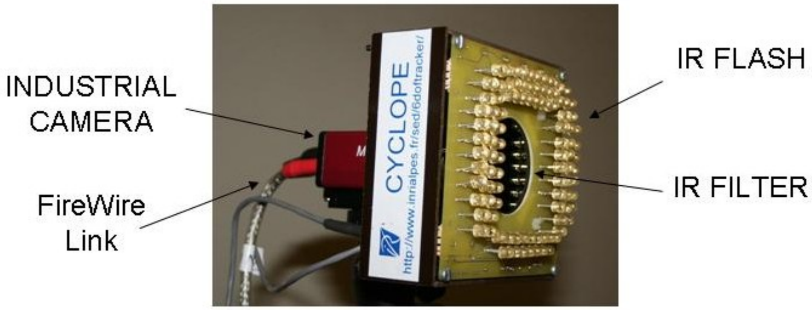
Marker-based Optical Tracking: Passive Targets

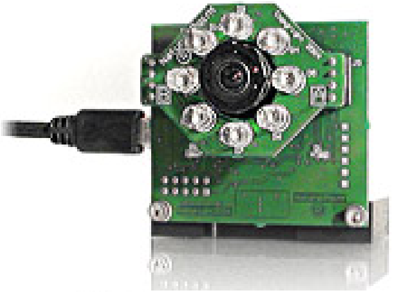


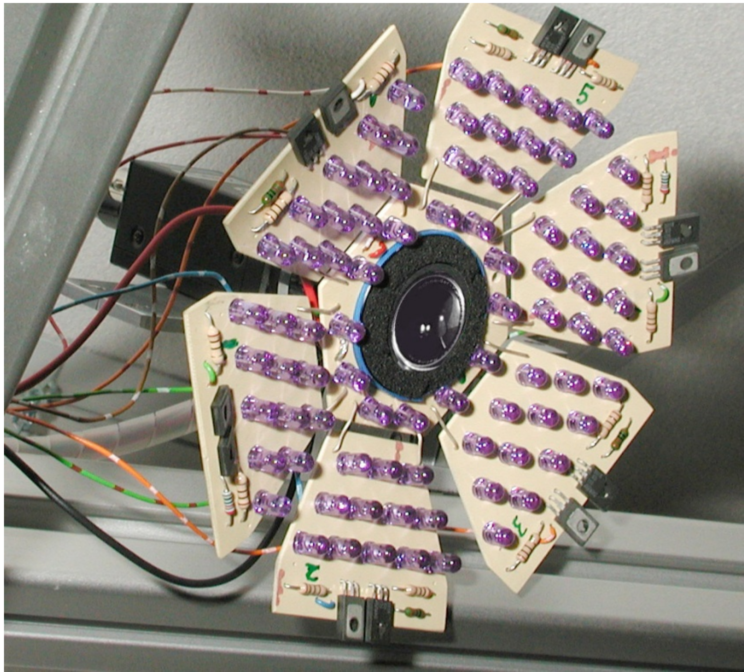
Overview: Passive Infrared-Optical Tracking Systems



Overview: Passive Infrared-Optical Tracking Systems

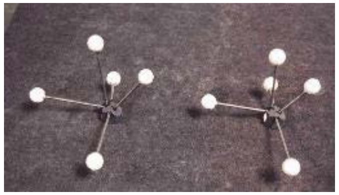






Optical Tracking - A.R.T.

Tracking camera:
- IR flash
- IR camera
- Embedded Linux System for image processing



Targets:
- Retroreflective spheres
- Unique distances/arrangement

Example: [Fingertracking]() (Dorfmüller)

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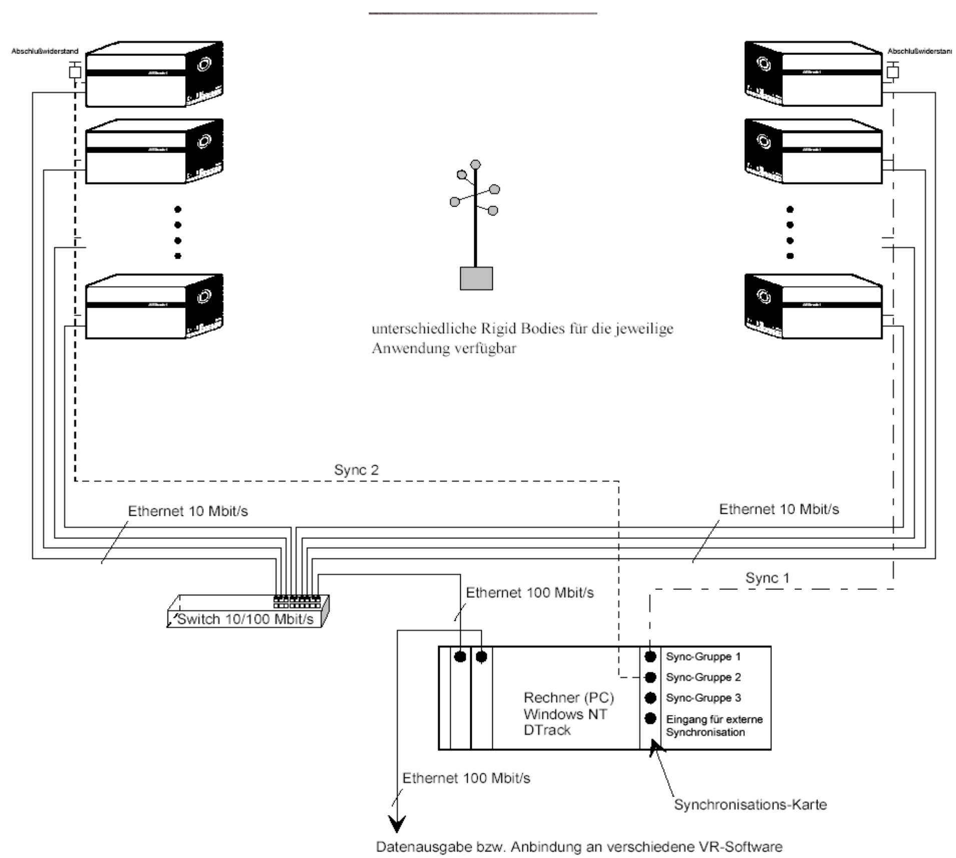
A.R.T. Tracking - Schema

- Multiple cameras
- Synchronization: external PC
- Autonomous image pre-processing
- Central processing: external PC



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Optical Tracking - Specifications

Model	Latency	Max. # of sensor	Range	Accuracy	Costs
A.R.T. Dtrack	20 - 40 ms	10	~ 6 m	250 µm; 0,4 degree	€ 30.000
ND Polaris (active)	20 ms	20	~ 3 m	350 µm	?
ND Polaris (passive)	20 ms	6	~ 3 m	100 µm	?
OptoTrak	20 ms	256	~ 3 m	100 µm	€ 64.000

All latency times without filtering

Prices: Optical Tracking Systems

- However, commercially available infrared-optical trackers are **not exactly affordable...**
  - **Vicon Peak** 6-camera system **€ 50,000** (approx.)
  - **A.R.T.** 4-camera *ARTrack2* package **€ 30,000** (approx.)
  - **PhaseSpace** 4-camera system **€ 25,280**
- Constant prices for more than ~10 years
- Clients:
  - Movie industry (Motion Capture)
  - Medical research
  - Industrial AR/VR applications & research
  - Not affordable for many other areas

TU Wien IMS: iotracker

- Self-assembled tracking cameras by using commercial parts
- connected via Firewire
- Combined tracking + application on 1 PC
- Scalable: 60Hz-200Hz
- Price: 1/3 – 1/5 of other commercial systems


iotracker
affordable infrared-optical pose tracking
TECHNISCHE UNIVERSITÄT WIEN
TU VIENNA
VIENNA UNIVERSITY OF TECHNOLOGY
1.5 - 3.0m
2.0 - 4.5m
2.0 - 4.5m
specifications
Update rate: 60 Hz
Latency: 18 - 40 ms
Jitter: < 0.05 mm / 0.02°
Accuracy: ± 0.5 cm
FireWire

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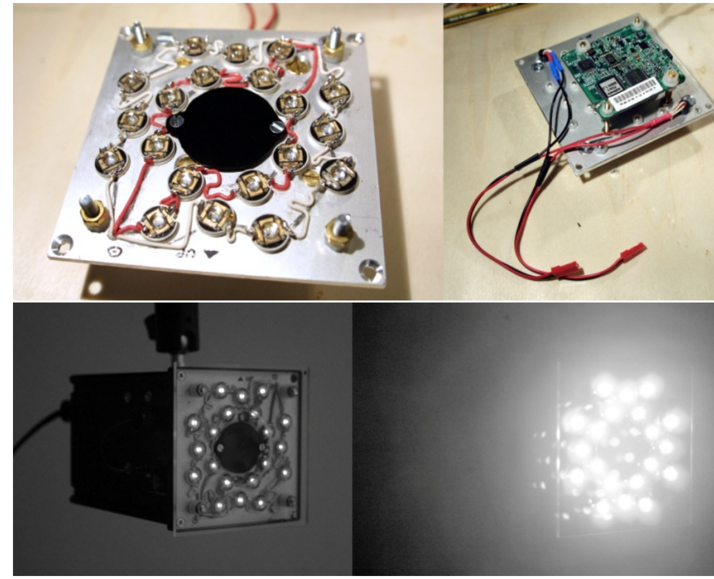
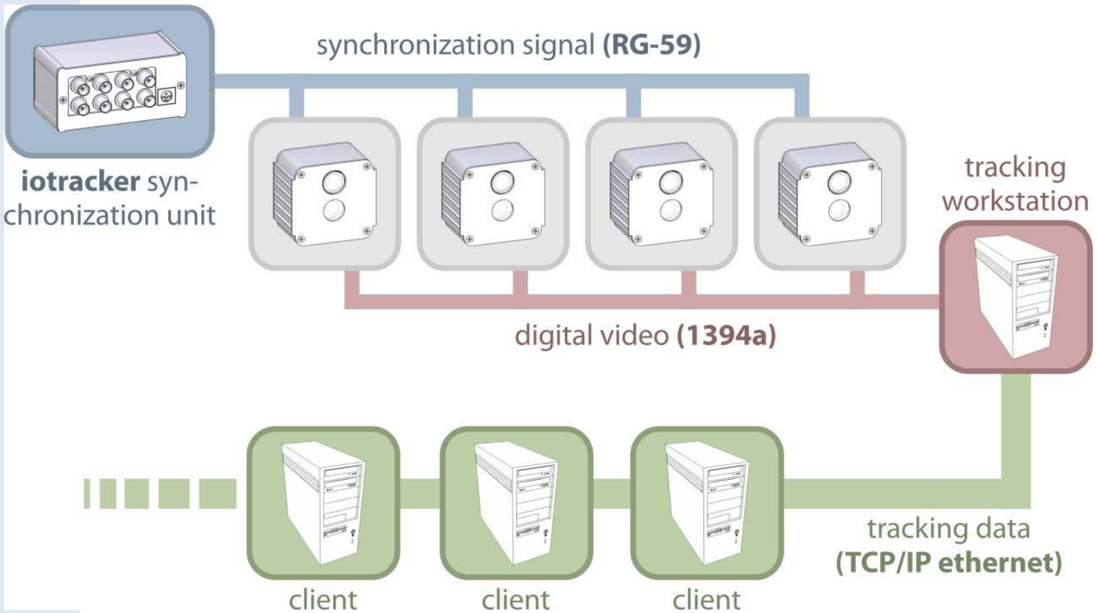
Camera Hardware





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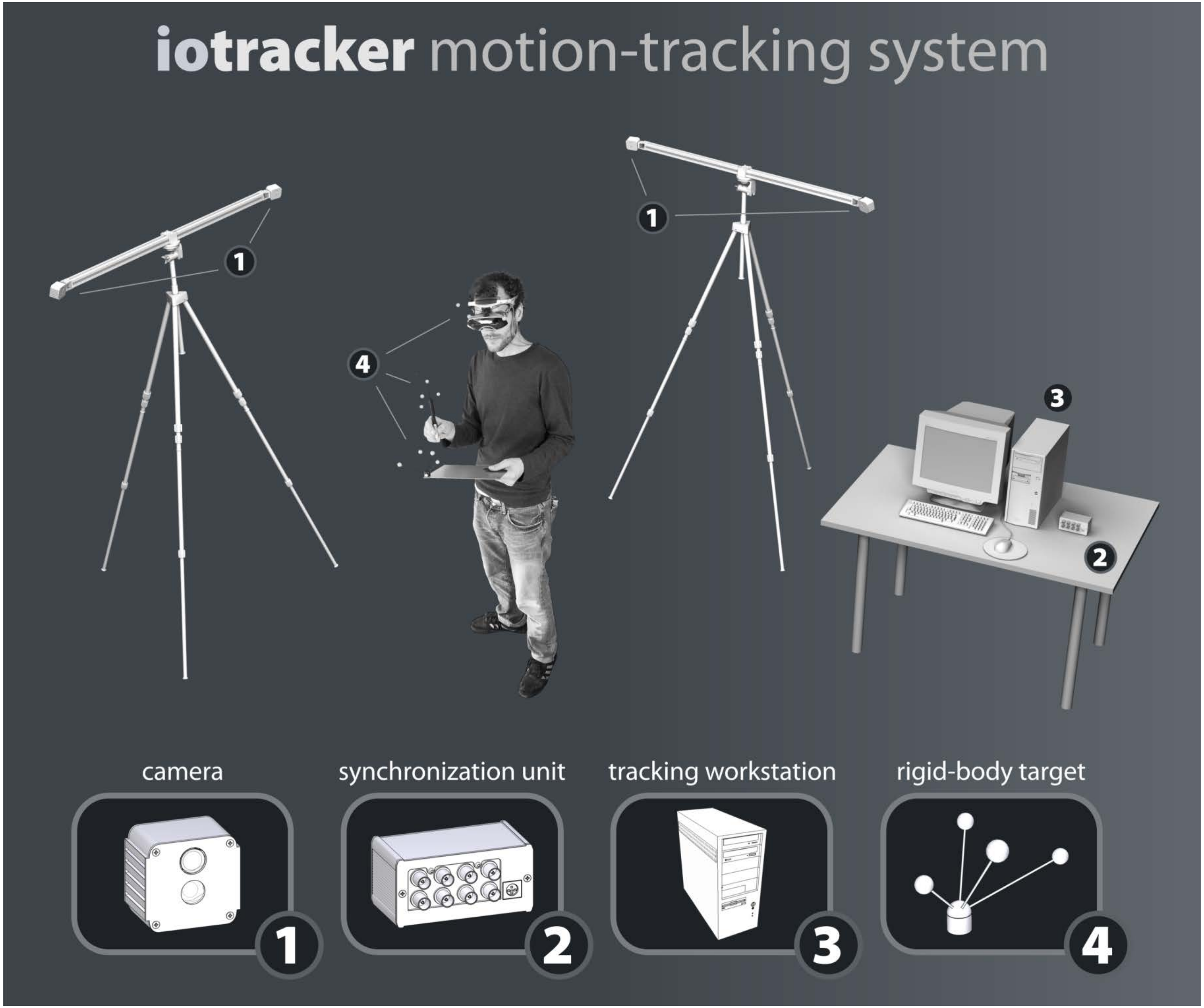
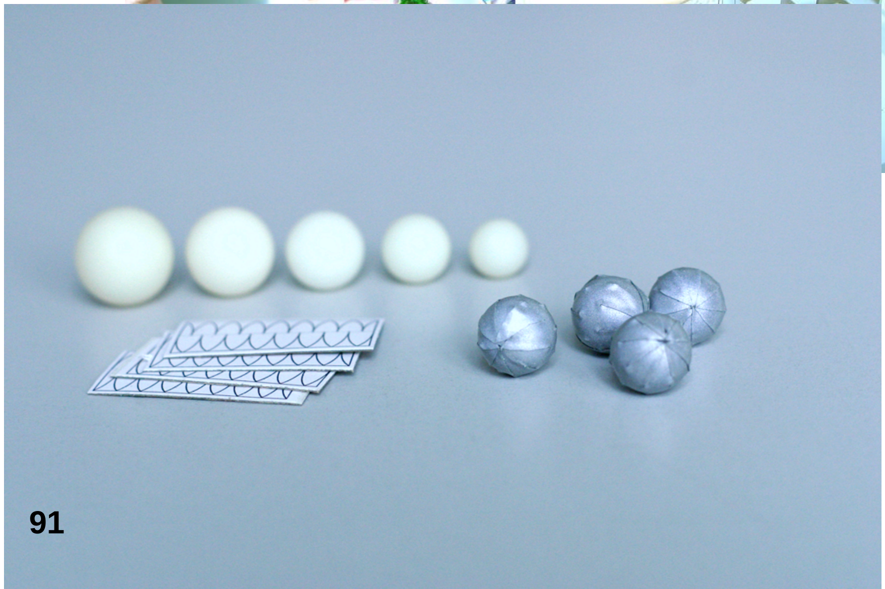


Retroreflective Markers



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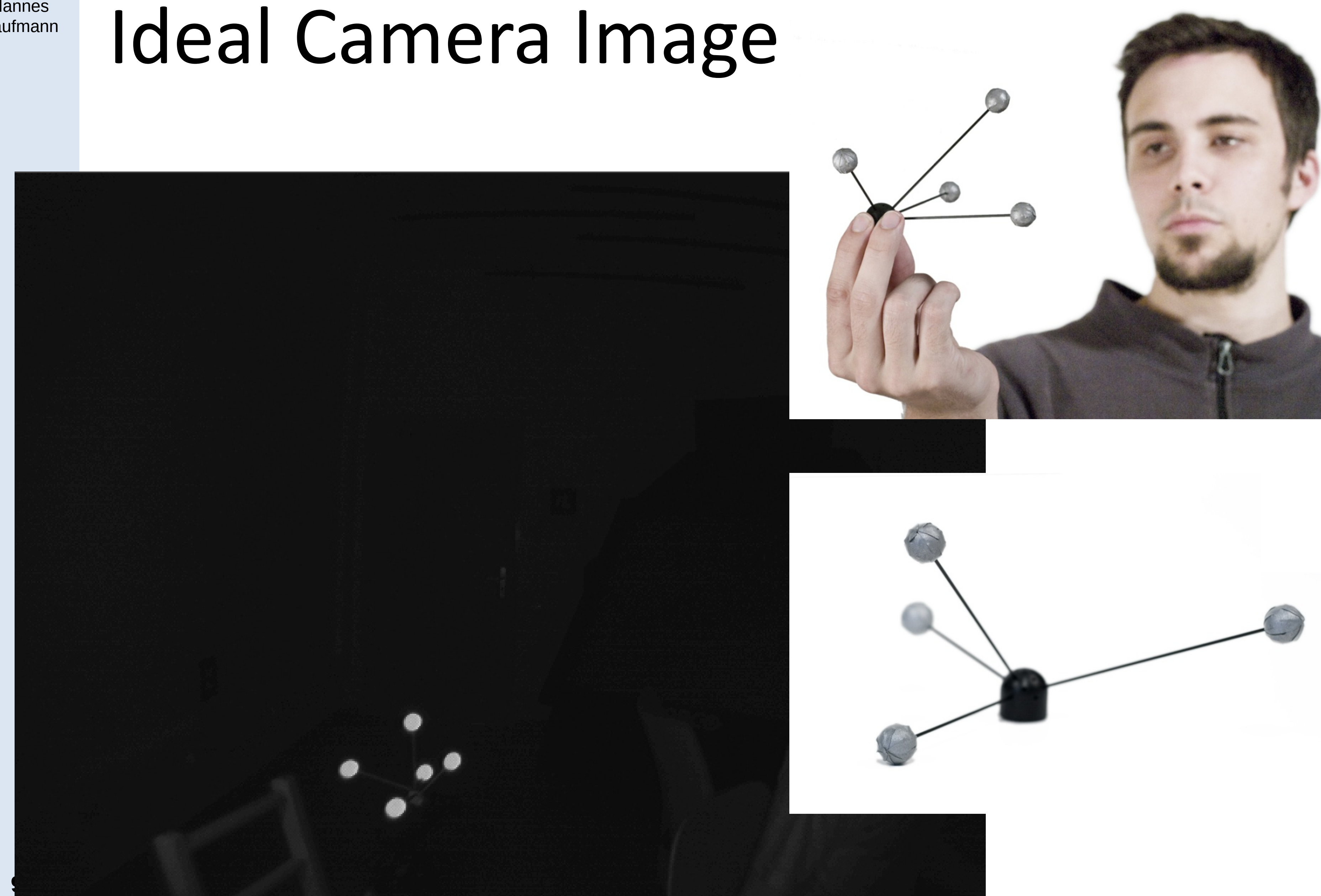
Ideal Camera Image



Optical Tracking System Design

1. Camera calibration (intrinsic, extrinsic parameters)

2. Segmentation & feature identification: detecting blobs
3. Feature correlation: finding multiple-view blob correspondences
4. Projective Reconstruction: acquire 3-DOF marker positions
5. Model-fitting: find pre-calibrated rigid constellations within the marker point cloud
6. Pose estimation: obtain 6-DOF pose (rotation/translation) for each rigid constellation

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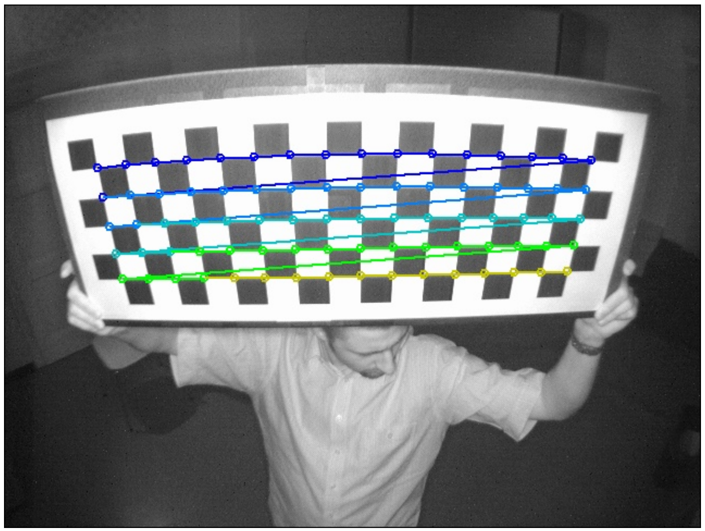
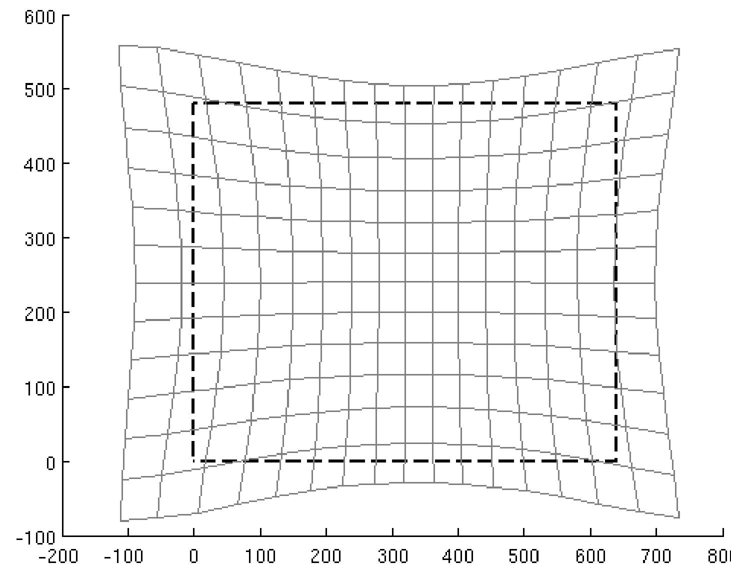
Camera Calibration (Intrinsic Parameters)



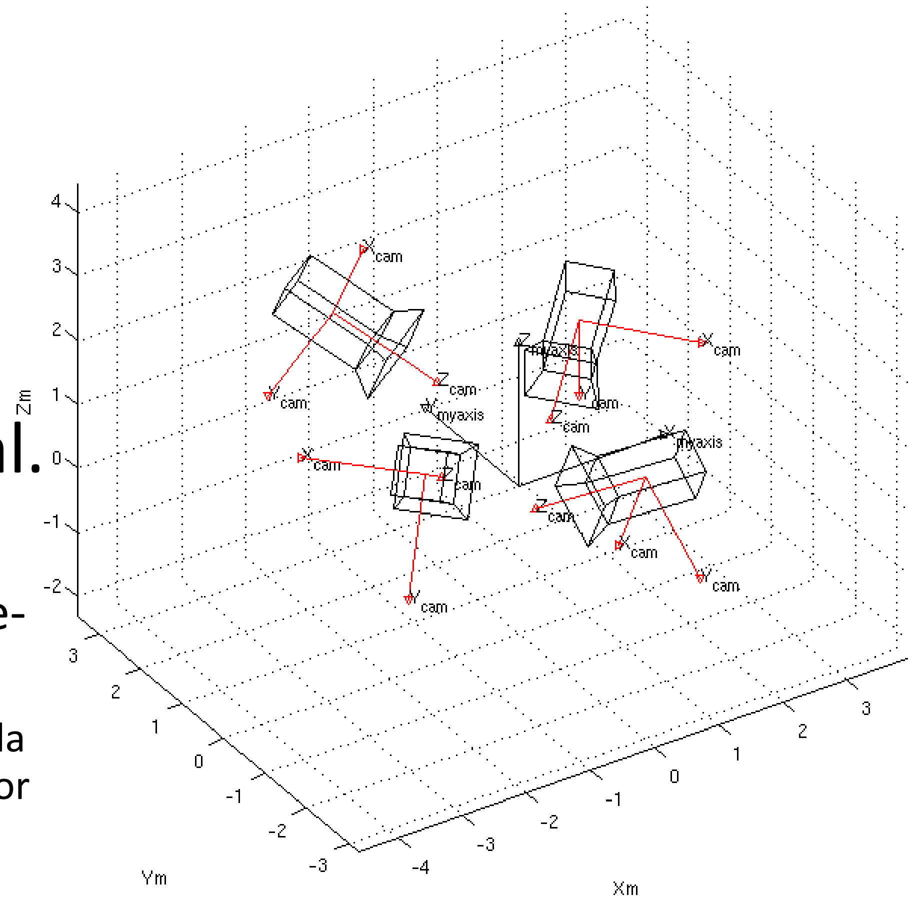


Non-linear lens distortion model *(Heikkilä 1997):*

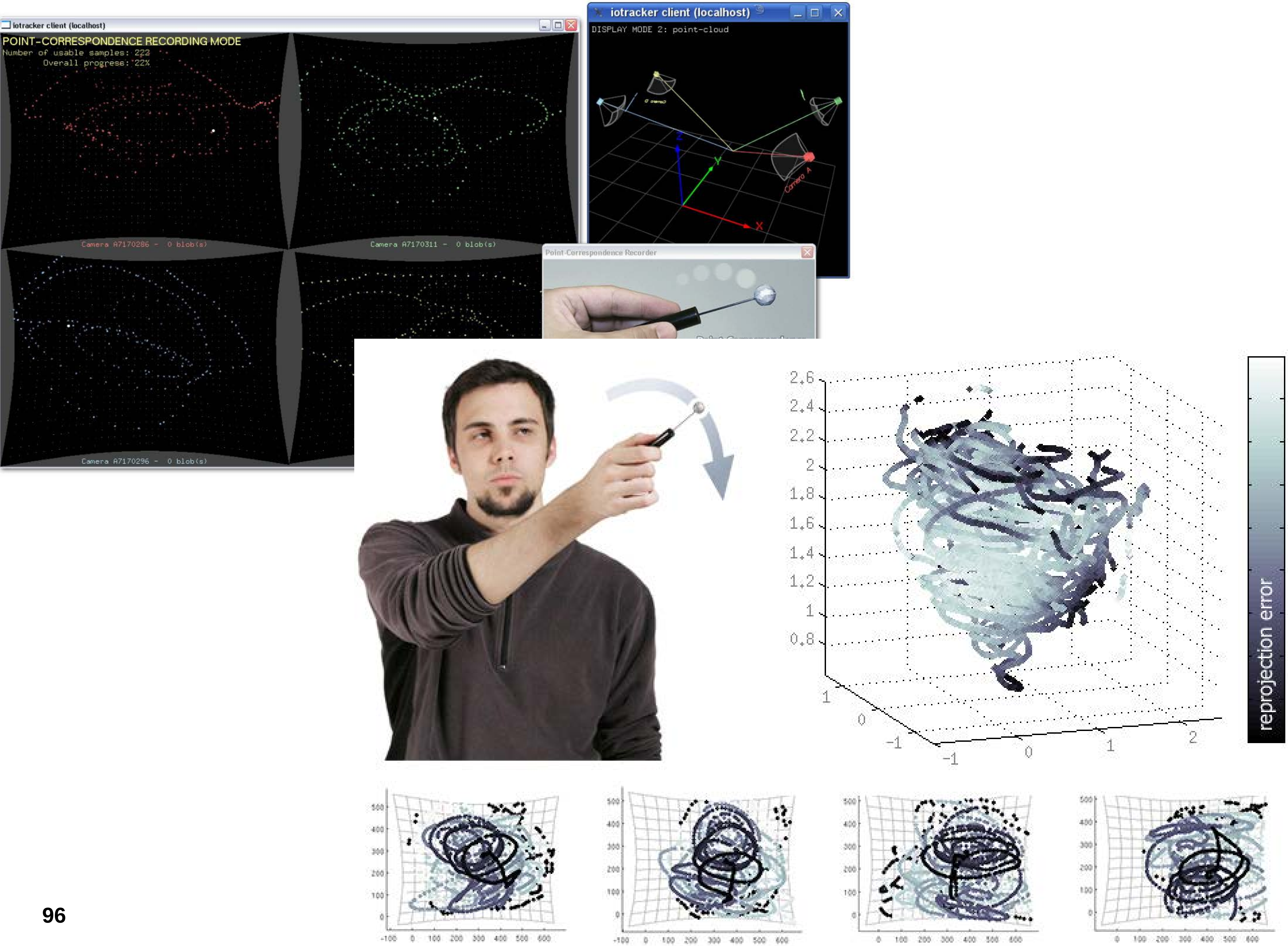
- Radial / tangential distortion
- Focal distance, …

Camera Calibration (Extrinsic Parameters)

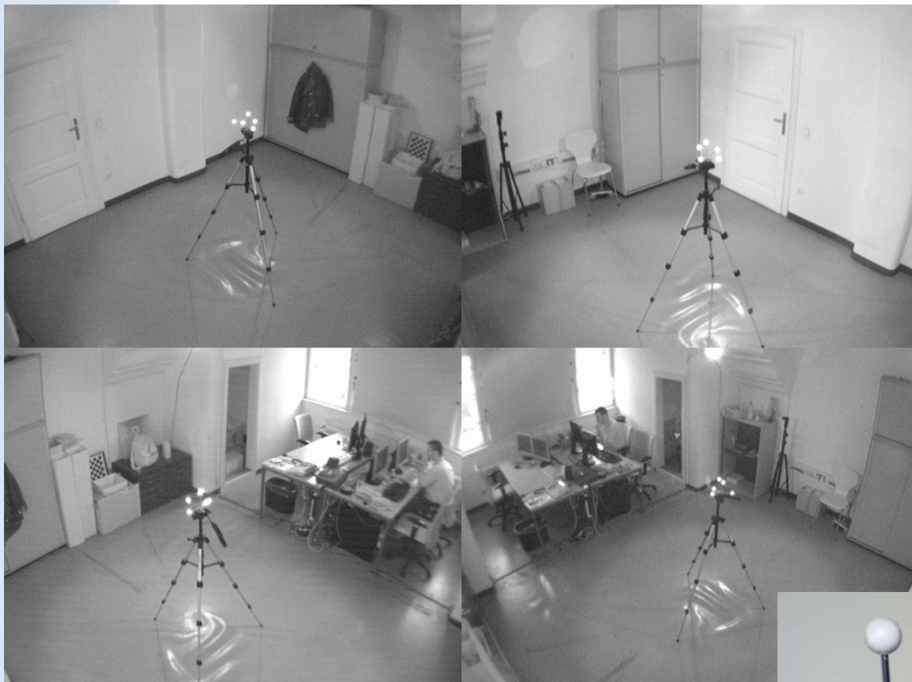
- Calculate position and orientation of cameras to each other and points in space
- We use the calibration algorithm by Svoboda et al. [*]
  - uses multiple-camera (>3) single-point correspondences

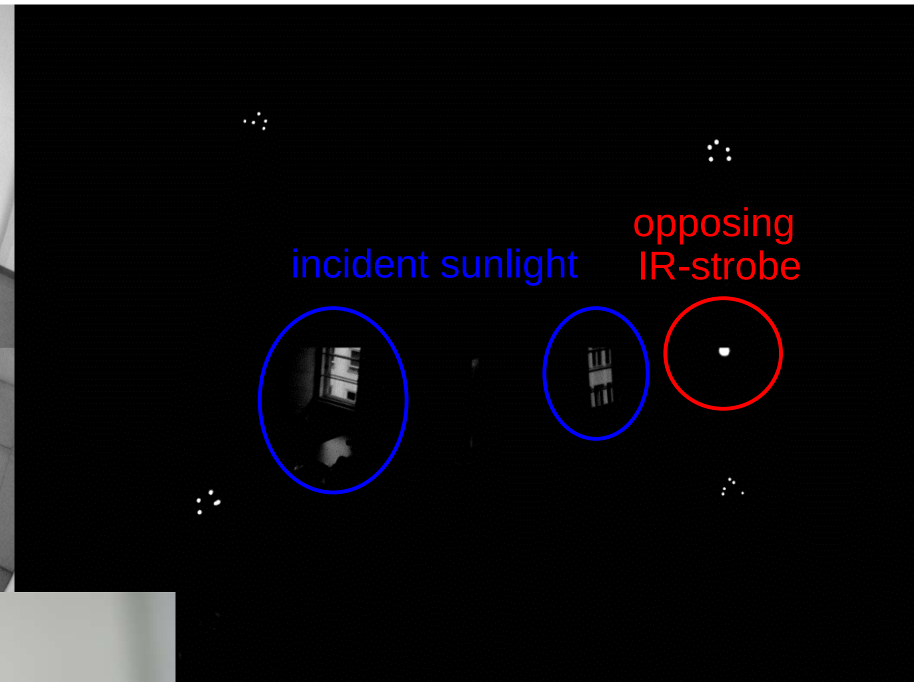


[*] Tomas Svoboda, Daniel Martinec, Tomas Pajdla
A Convenient Multi-Camera Self-Calibration for Virtual Environments (2005)


iotracker client (localhost)
POINT-CORRESPONDENCE RECORDING MODE
Number of usable samples: 222
Overall progress: 22%
Camera A7170286 - 0 blob(s)
Camera A7170311 - 0 blob(s)
Camera A7170296 - 0 blob(s)
iotracker client (localhost)
DISPLAY MODE 2: point-cloud
Point-Correspondence Recorder
reprojection error

Blob Detection





Shutter: 1/31s
Maximum Gain

Shutter: 1/200s
Low Gain

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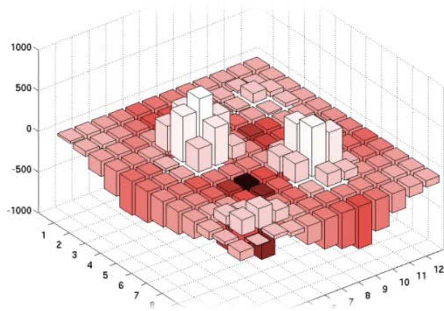
Blob Detection



Two-step procedure:

- Binary thresholding to discover blob candidates.
- Weighted-luminance centroid computation, using per-pixel difference matting
  - Background model is trained beforehand
- Problem: overlapping blobs
  - Solutions: contour-based segmentation or Hough circle finder

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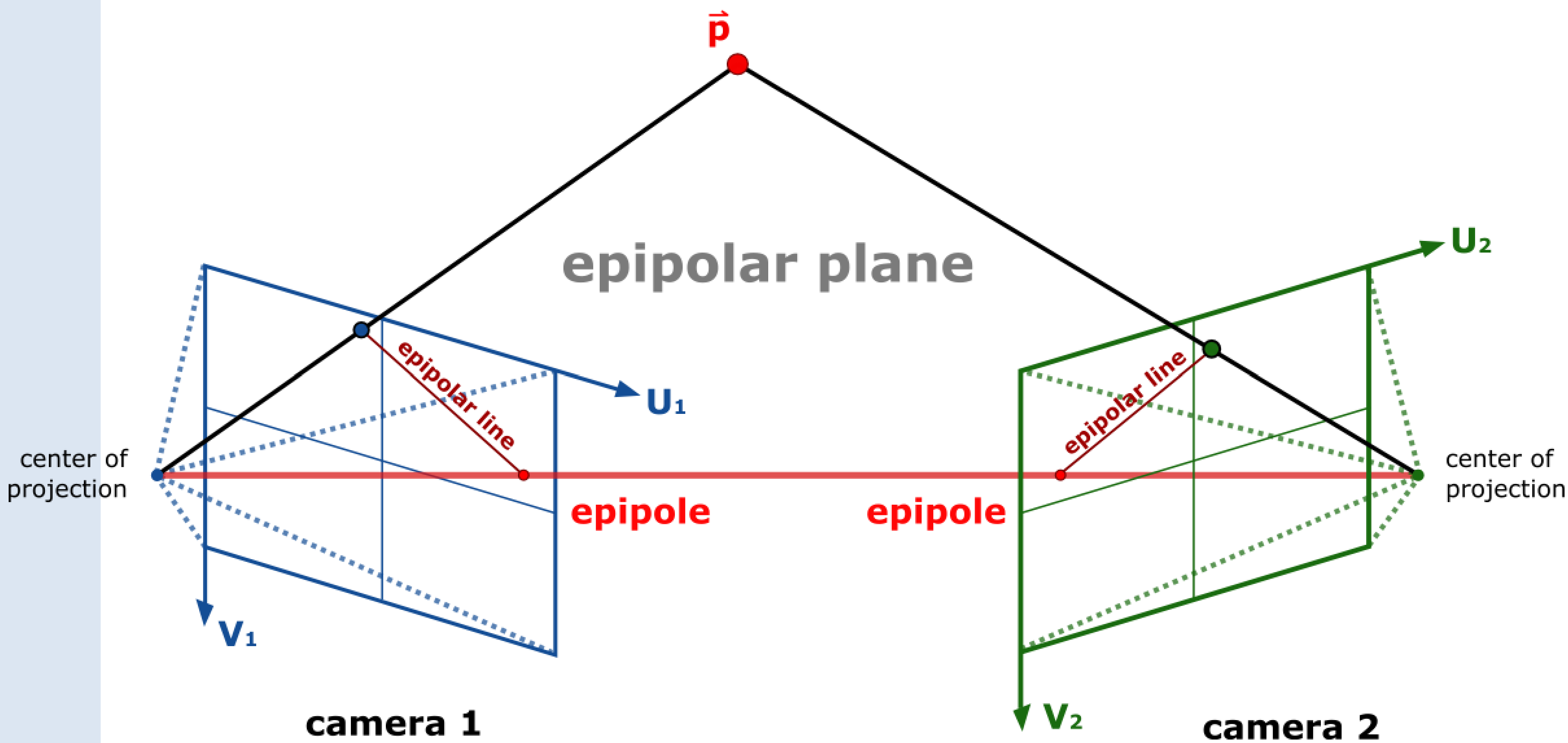
Epipolar Geometry



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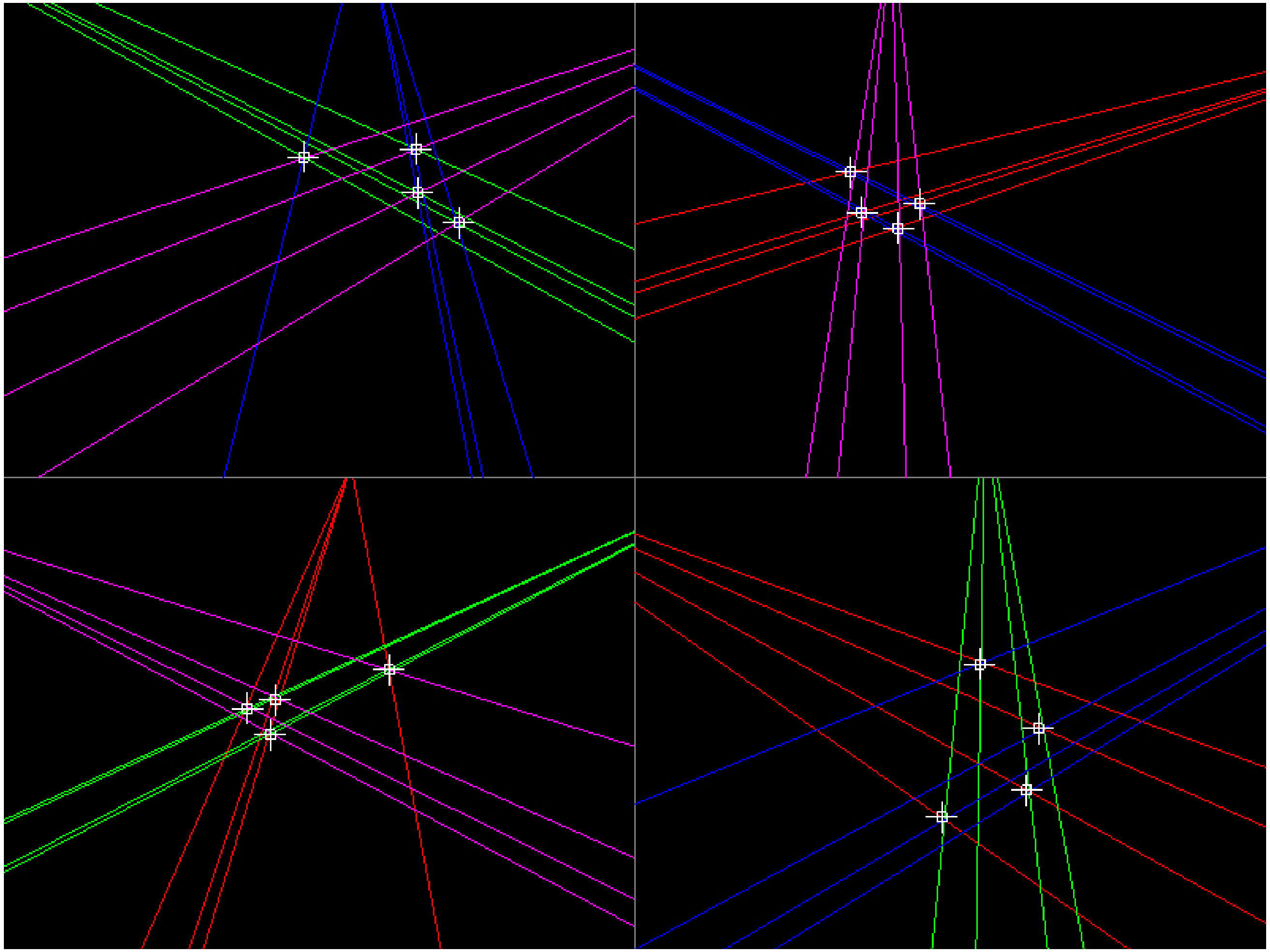
Epipolar Geometry: Feature Correlation



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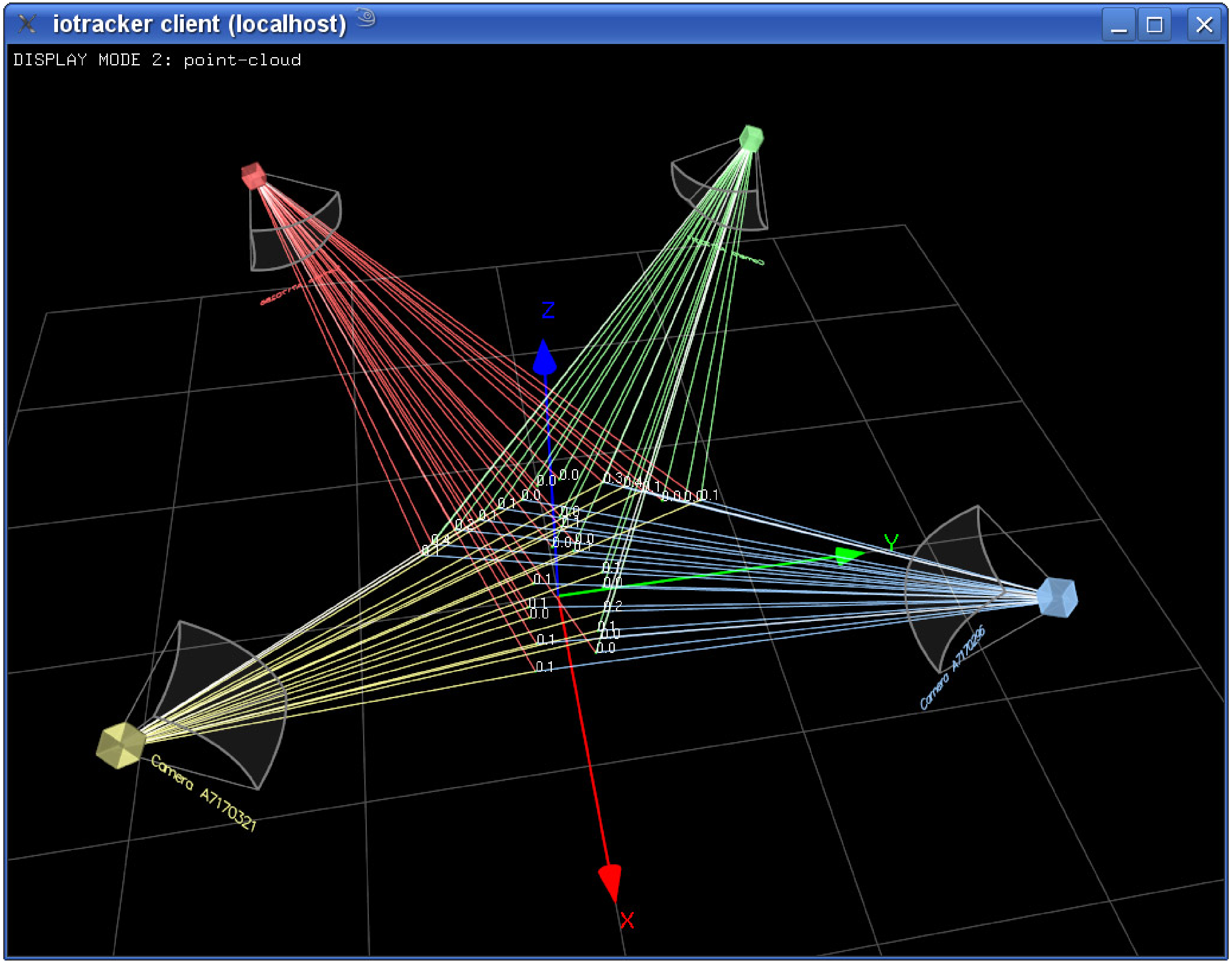
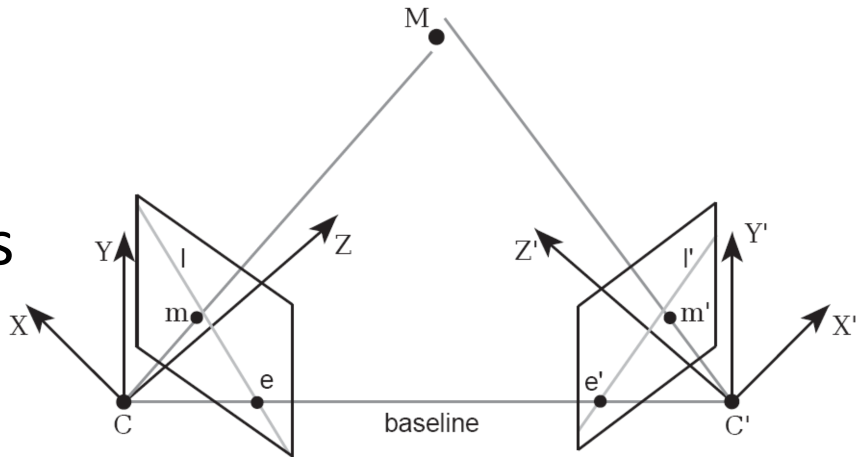
Epipolar Geometry:

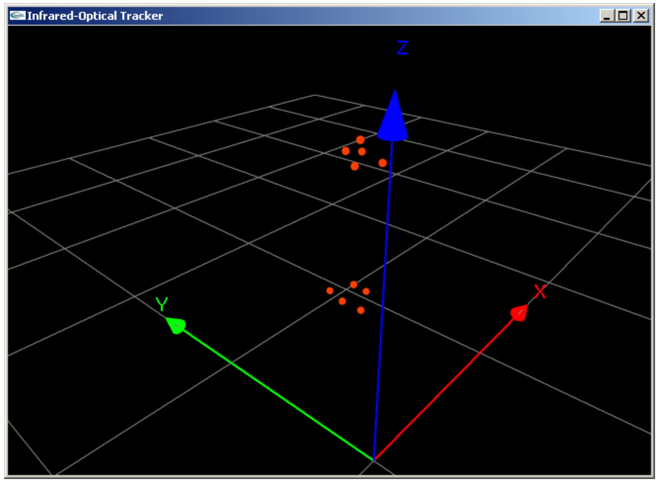


Projective Marker Reconstruction

- Rays do not exactly intersect (in practice)
- Currently using least-squares approach for projective reconstruction
- Small number of markers (<40): Sparse bundle adjustment (Levenberg-Marquardt) to refine results (recursive)

→ 3D Point cloud





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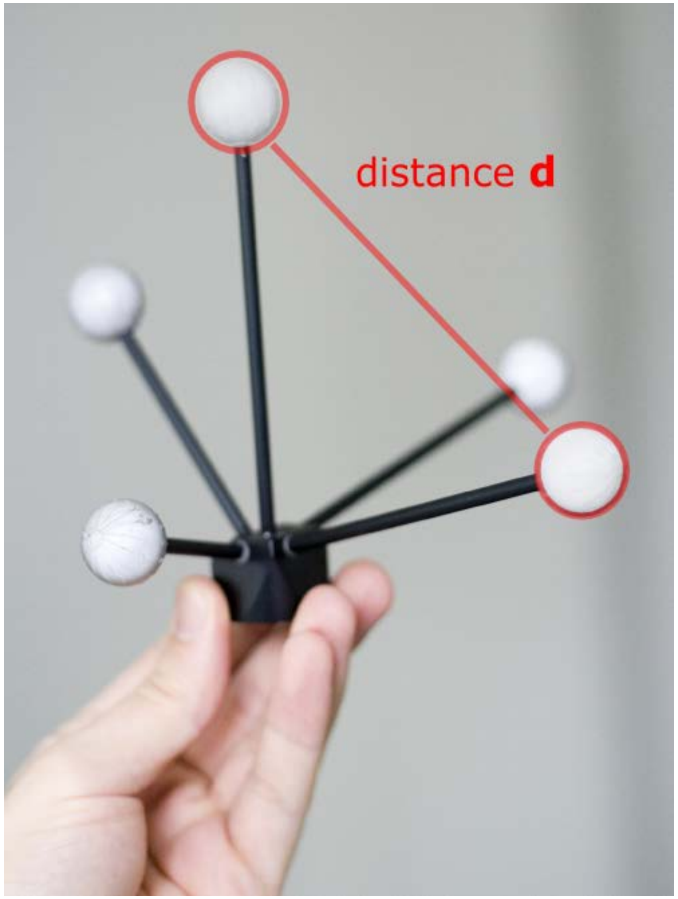
Model-Fitting

- pre-compute intra-constellation marker distances
  n! / [2*(n-2)!] entries

<u>Once per frame/constellation:</u>

- for every pair compute the Euclidean distance
  (about 5000 computations for 100 markers)
- Selection out of multiple hypotheses



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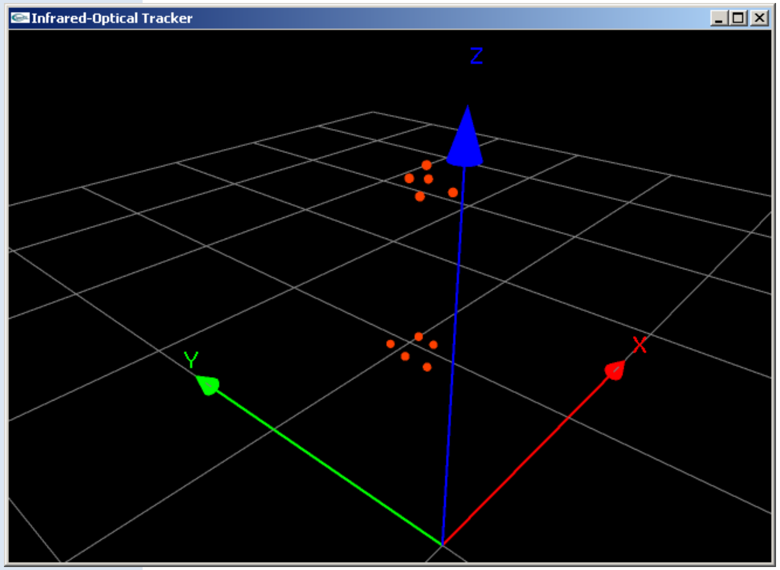
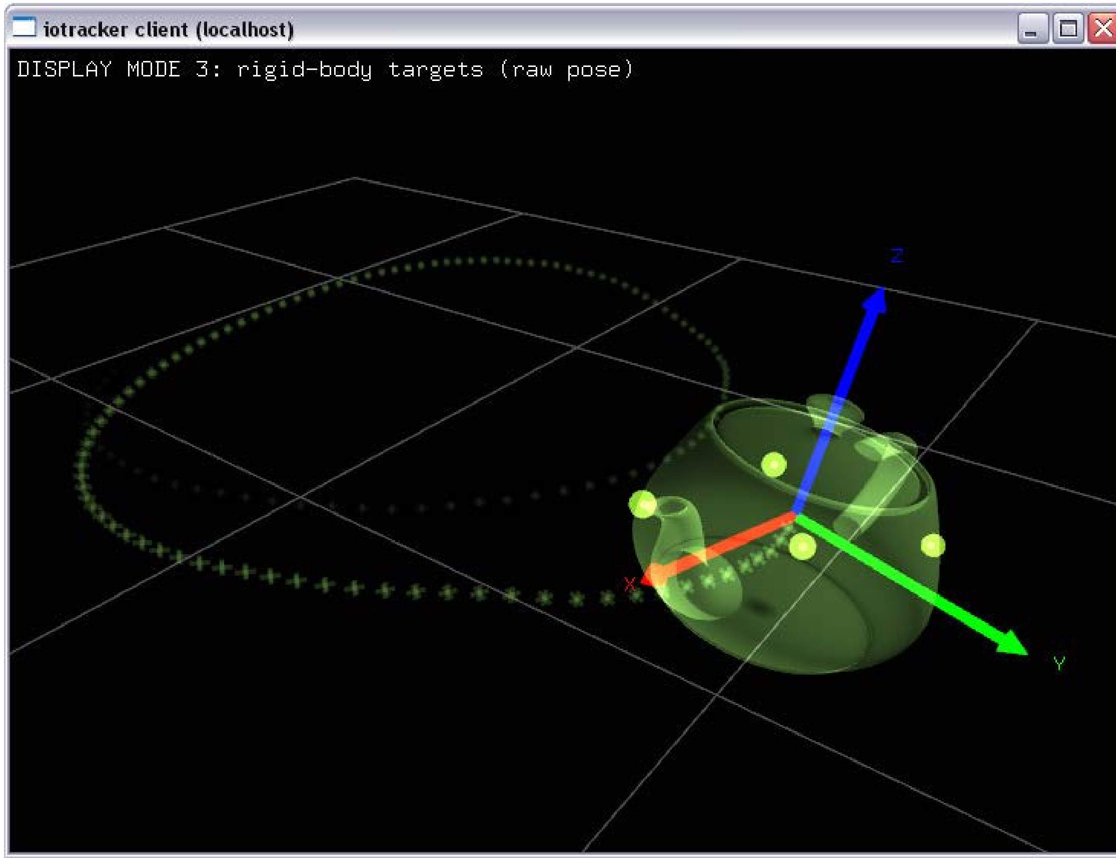
6-DOF Pose Estimation

- Based on stored target model:
  Perform a **least-squares estimation** of rotation and translation.





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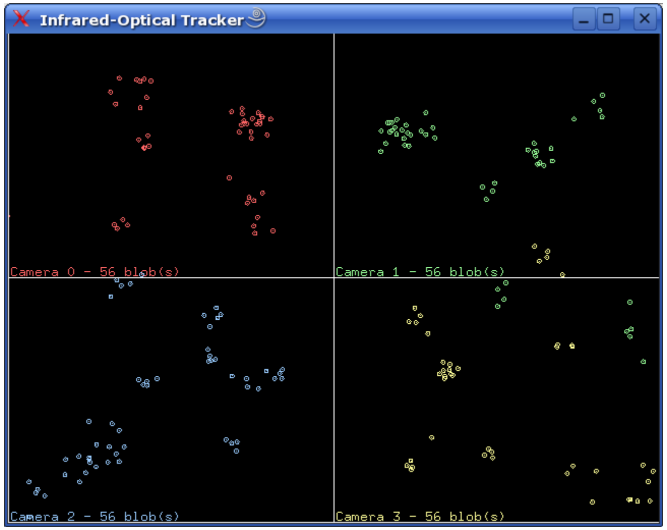
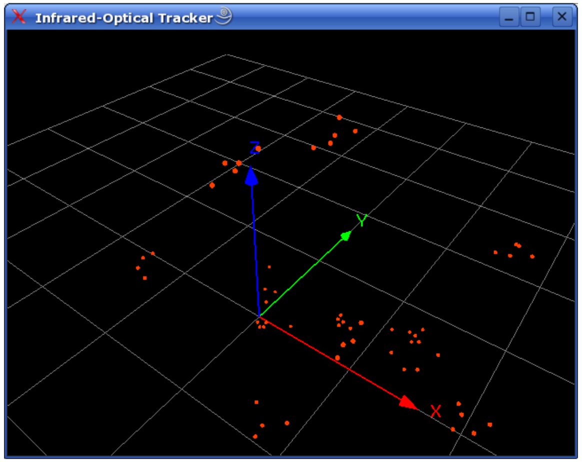
Results: Performance

<u>Artificial benchmark:</u>

- 4 cameras
- 224 blobs (56 per camera), with simulated 2D jitter (gaussian noise), no segmentation
- 56 markers
- 8 rigid constellations (consisting of 36 markers)
- all 8 constellations tracked at 60Hz with approx. 70-75% combined CPU load (2.16 GHz Intel T2600)





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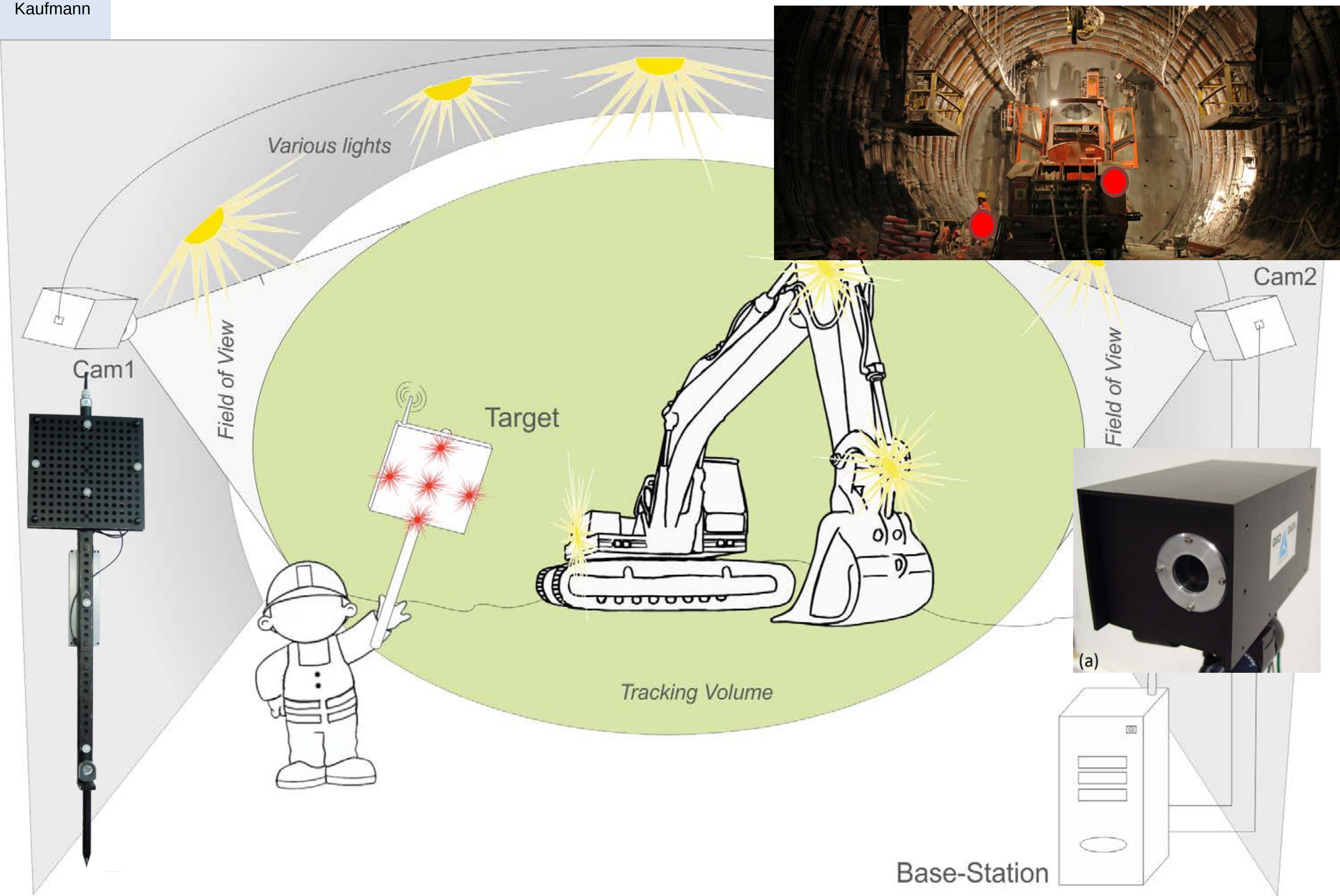
Measurements in a Tunnel



Consumer Devices

Usually tracking in small area (monitor):

- Dynasight (2500 USD)
- TrackIR (150 USD)
  - 6DOF
- OptiTrack
  - >100fps
  - On-board blob detection

Active/Passive Marker Tracking

- Advantages
  - Very accurate (millimeter or sub-millimeter)
  - Supports tracking in a large volume
  - allow for untethered tracking
- Disadvantages
  - Requires active (LED) or passive markers
  - Occlusion problem

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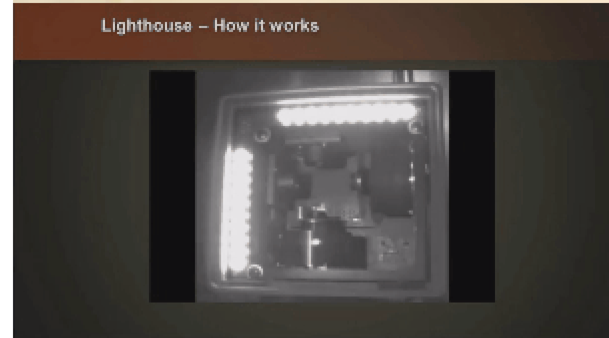
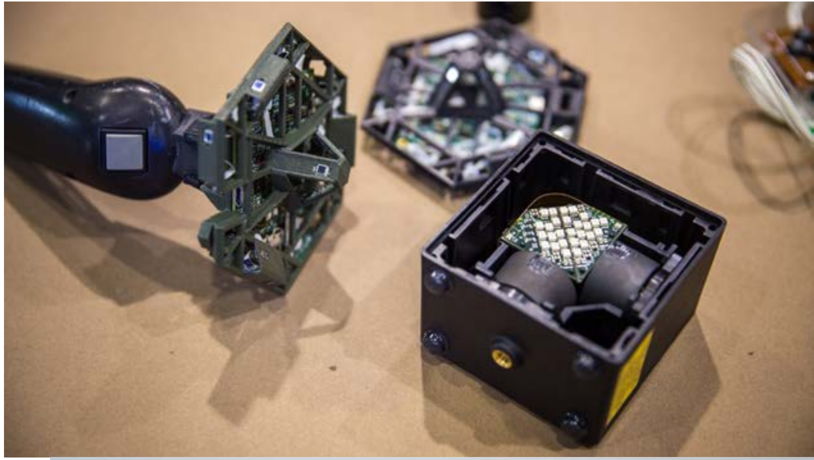
HTC Vive Lighthouse

- Inside-Out Trackingsystem
- 2 line lasers per base station + synch IR LEDs (every 8.3ms)
- Photo diodes on HMD and controller
- Time difference -> angle to base



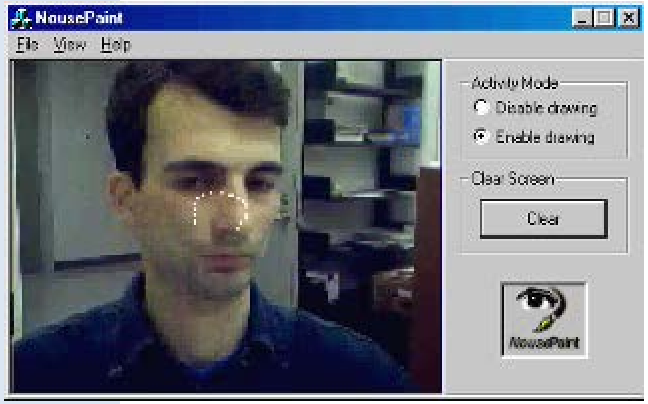
Steam VR (Valve) Lighthouse Tracking



- 1006Hz inertial sensor mainly used for tracking (hybrid tracking!)
- 60Hz optical tracking update rate
- 1ms worst case latency (head), 2.7ms (controllers)
- Very precise. Static jitter: 0.3mm lateral, 2.1mm in distance direction (single base)

Source: Oliver Kreylos http://doc-ok.org/?p=1478

Optical Tracking without Markers



Natural Feature Tracking (NFT)

- More difficult than marker tracking
  - Markers are designed for their purpose
  - The natural environment is not…
- Less well established methods
  - Every year new ideas are proposed
- Slower than marker tracking

Idea:

1. Detect reliable features in image (e.g. corners, lines, …)
2. Compare with reference image/3D model

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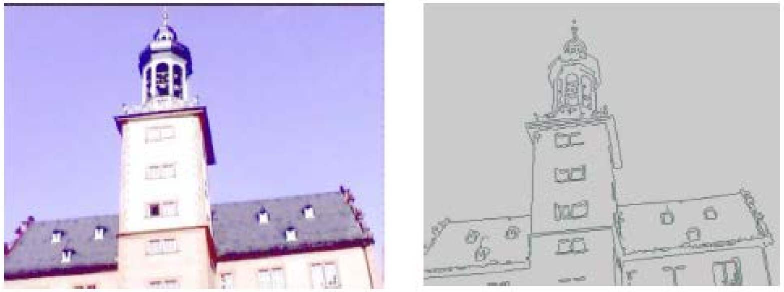
Many different methods and combinations

- Features
  - Points
  - Edges
  - Horizon
- Sensor fusion
  - Gyroscopes
  - Accelerometers
  - GPS, …
- Requires Initialization!
- Not (very) robust
  - Sensor fusion
  - Recovery methods

Azuma, '99



Kretschmer et al., '02

Ribo et.al., '02

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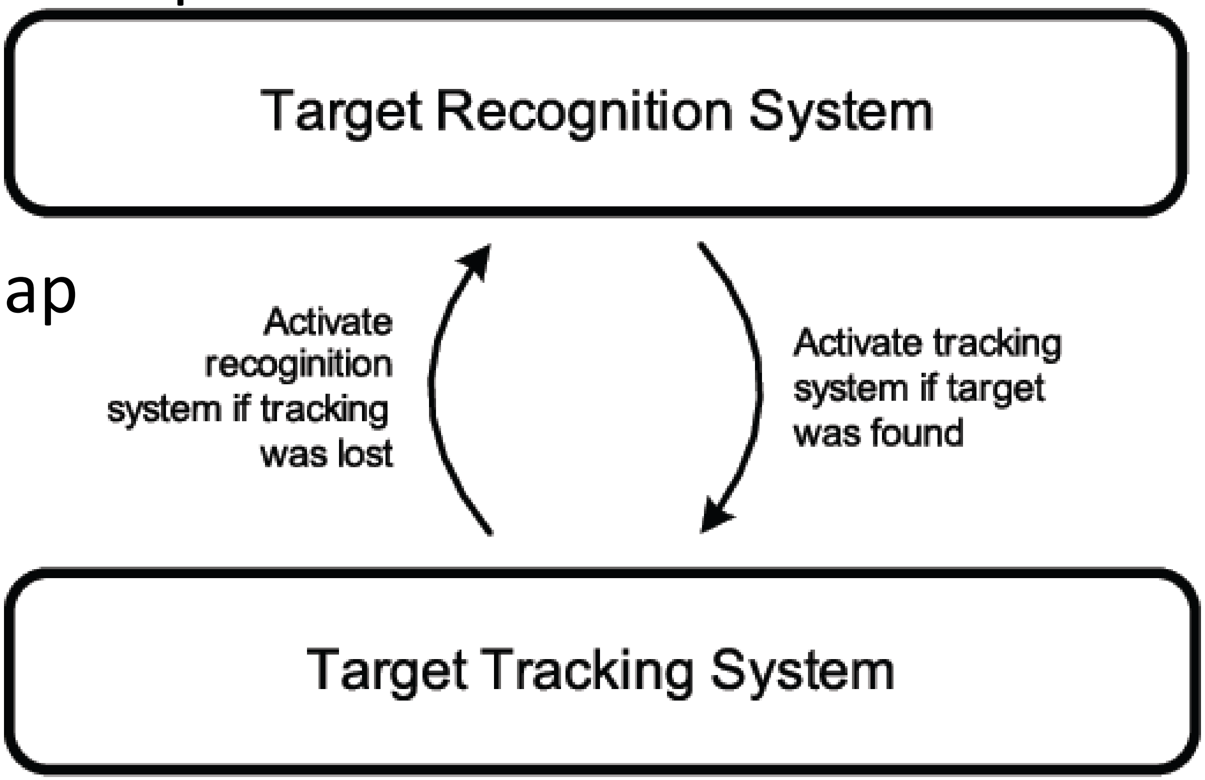
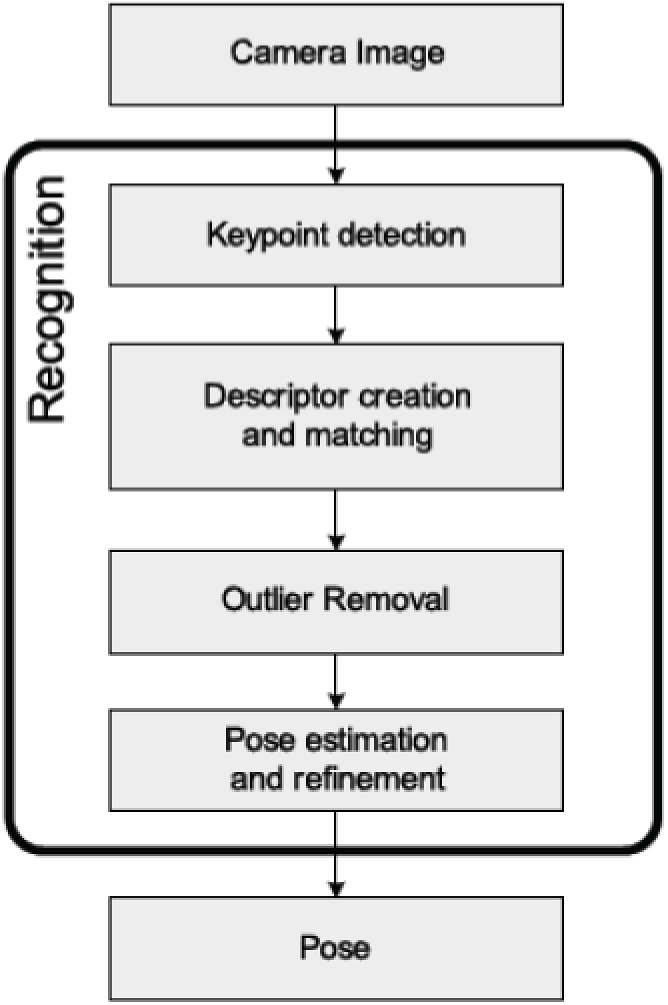
NFT - Initialization vs. Tracking

- Initialization = Recognition
  - Computationally expensive
  - Required at startup
- Tracking
  - Fast and cheap
  - Robust
  - Accurate



Detection in Every Frame

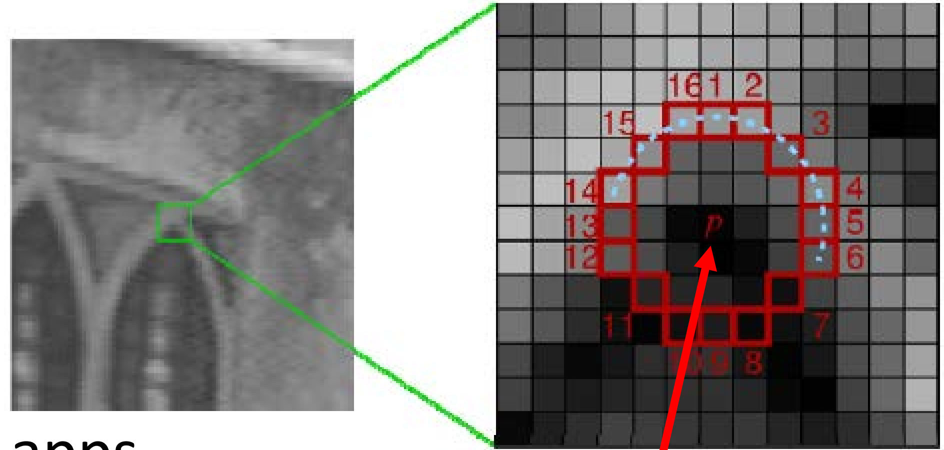
- This is what most „trackers“ do…
- Targets are detected every frame
- Popular because detection and pose estimation are solved simultaneously



Natural Feature Tracking: Examples

- EPFL Book: Video1, Video2
- Stricker: ISMAR Demo
- Reitmayr: Cambridge Going-out Demo
- PTAM on iPhone
- 13th Lab: SLAM and Room measurements
- InsiderNavigation: Indoor Navigation at Airport

FAST Corner Detector



* [Rosten, 2005]

- FAST corner detector
  frequently used for mobile apps
- Produces very stable features
- Simple and fast algorithm to compute a feature:
  If *n* contiguous pixels are all brighter than the nucleus (center pixel) by at least treshhold *t* or all darker than the nucleus by *t*, then the pixel under the nucleus is considered to be a feature. - Best results with Fast-9 (*n*=9)
- Robustness by using FAST on a database of different scales

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PTAM: Algorithm Overview

- Georg Klein and David Murray. PTAM: Parallel Tracking and Mapping, 2007.
  PTAM is a SLAM algorithm (Simultaneous Localization and Mapping)
- Tracking and mapping are separated and run in two parallel threads
- Mapping is based on keyframes, which are processed using batch techniques (Bundle Adjustment)
- The map is densely initialized from a stereo pair
- Large numbers (thousands) of points are mapped

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PTAM in the Hofburg Festsaal

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PTAM Tracking - Part 1

A new frame is acquired from the camera, and a prior pose estimate is generated from a motion model

Map points are projected into the image according to the frame’s prior pose estimate

A small number (50) of the coarse-scale features are searched for in the image

PTAM Tracking - Part 2

The camera pose is updated from these coarse matches

A larger number (1000) of points is re-projected and searched for in the image

A final pose estimate for the frame is computed from all the matches found

Natural Feature Tracking by Detection

SIFT: Scale-invariant feature transform [Lowe, 1999]

- State of the art for object recognition
- Known to be slow
- Typically used off-line
- Invariant to uniform scaling, orientation, affine distortion, and partially invariant to illumination changes

Ferns [Ozuysal, 2007]

- State of the art for fast pose tracking
- Memory intensive
  - requires ~10x too much memory for phones
- Long training phase

NFT with SIFT on a Mobile Phone

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Natural Feature Tracking

- Highly desirable to get rid of markers
  - More beautiful setups
  - More acceptance from commercial side
- Very precise

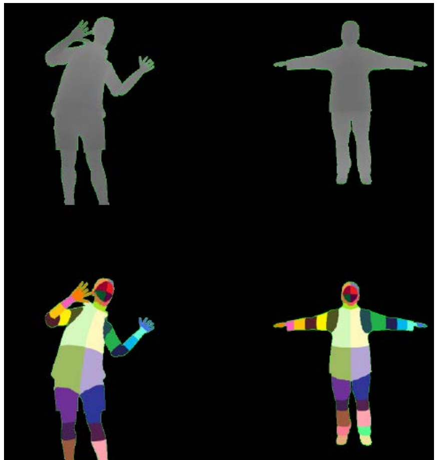
- However, suffers from
  - Light conditions (spotlights)
  - Environmental changes
  - Camera's field of view
  - Large occlusions
  - Performance issues
    - Low CPU performance
    - Memory requirements
  - Bad or slow cameras (blur)

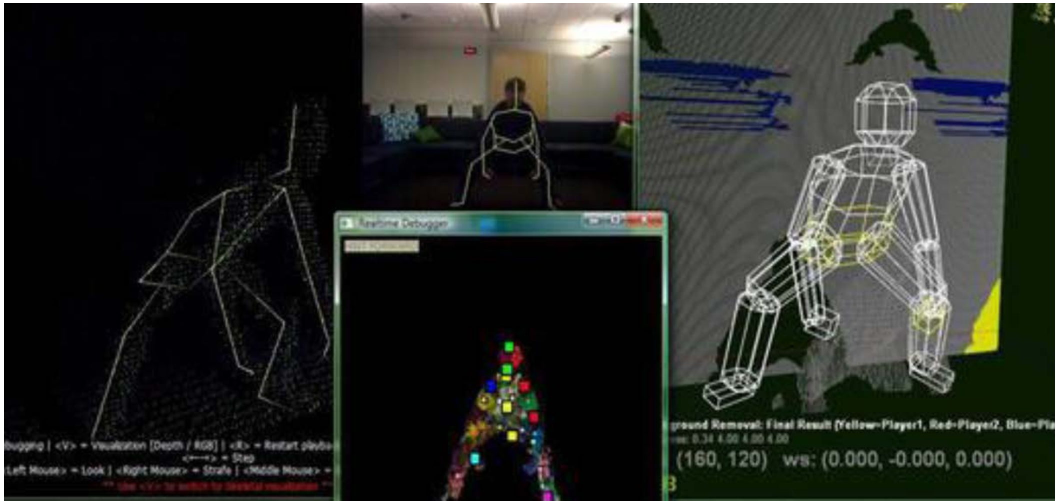
Depth Cameras

- 3 different technologies to capture an RGB + depth (RGBD) image with a single camera
  - Structured Light
  - Time of Flight (ToF)
  - Light Field Camera

Structured Light:
e.g. Microsoft Kinect

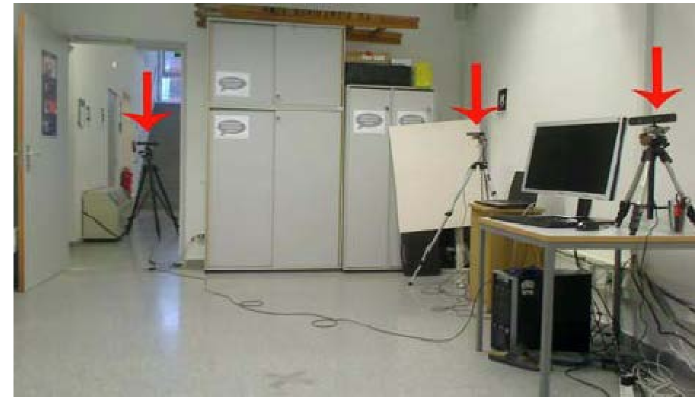
- 3D Sensor“ developed by Primesense
  - projects infrared pattern onto scene
  - detects pattern shift in camera image
  - 9 sub-regions with „random“ pattern
- Heavy machine learning to „guess“ pose
  - Mocap studios generated images, filmed people

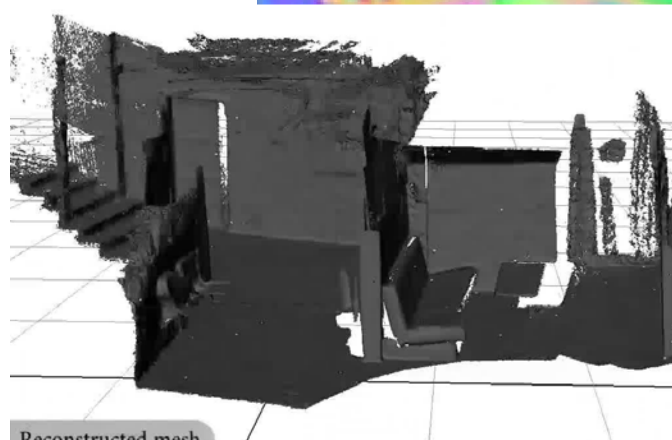




Some Kinect Projects

- Wide Area Tracking with Multiple Kinects
- Reconstruction – Kinectfusion
- Profitex – Large Scale 3D Reconstruction for Firefighters





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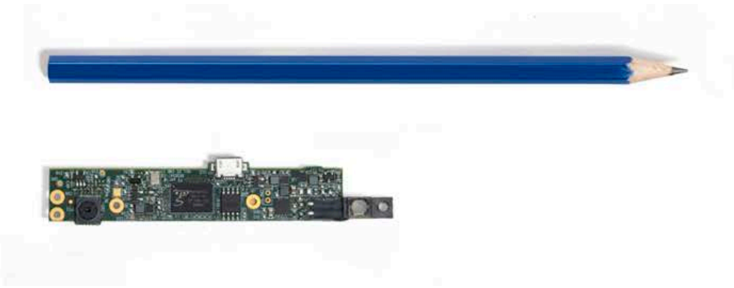
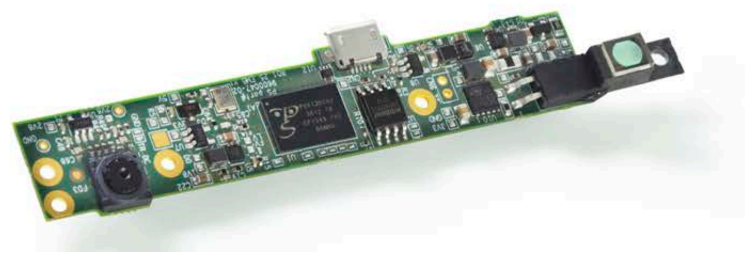
Mobile Kinect-Like Sensors

- Primesense Capri (bought by Apple)

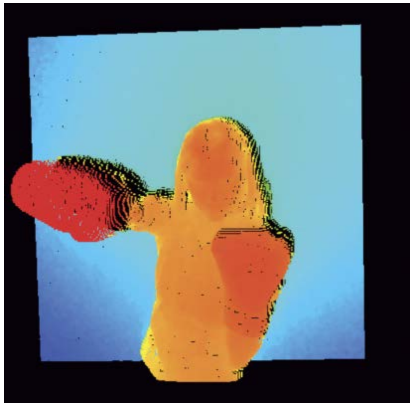




- Structure Sensor

Time of Flight Cameras

- Compute time of flight of IR pulse for each pixel
- Output depth image in addition to RGB
- Usually 0.5 - 7m range (or 7-14m etc.)
- Usually 8-bit depth resolution
  -> range split into 256 parts
- Currently max. 1MP resolution for depth image
- New possibilities for new applications



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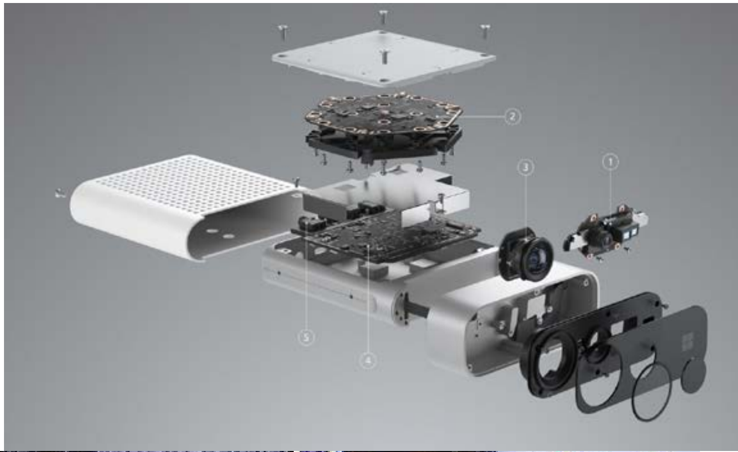
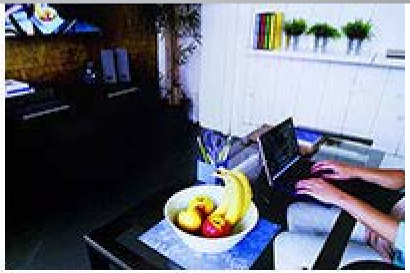
MS Azure Kinect

- Time-of-Flight Sensor
  - 1024x1024 px depth image, 120° FOV
  - 3840x2160 (RGB camera), 90°x59° FOV
  - 30 Hz
  - Range: 0.5–5 meters
  - IMU, 7 microphones (array)



Infrared in V2

Depth sensing in V2



1080p color camera in V2

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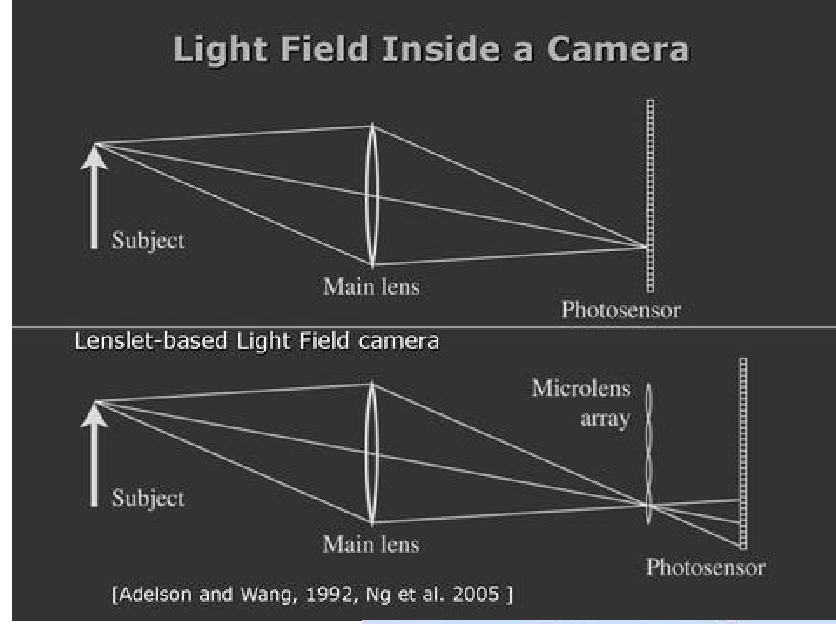
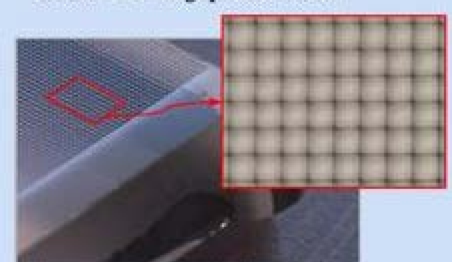
Light Field Camera (Plenoptic camera)

- is a camera that uses a microlens array to capture 4D light field information about a scene
- Allows reconstruction of the whole light field situation



Kodak 16-megapixel sensor



125µ square-sided microlenses

4000x4000 pixels; 292x292 lenses = 14x14 pixels per lens

Light Field Cameras

- Cameras: Raytrix, Lytro
  e.g. Raytrix R5, 1000x1000 resolution
  (2Kx2K sensor, grayscale), 60Hz, dual GigE, >100 depth layers

- Interactive Examples: http://lightfield.stanford.edu/lfs.html

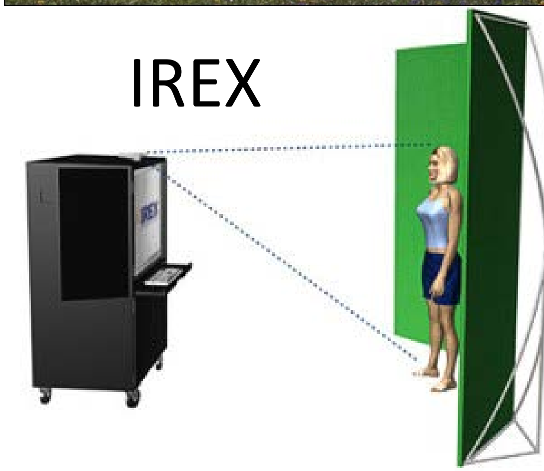
- Enables applications such as
  - Changing focus
  - Deblurring an image
  - Depth image computation

- Slides about light fields:

http://graphics.stanford.edu/courses/cs478/lectures/02272012_lightfields.pdf

Low-cost Gesture Recognition

IREX



Low cost for various applications:
Kinect / SONY Playstation Eye Toy for Rehabilitation

Motion Capture

Motion Capture Technologies:

- Exoskeleton (Mechanical)
- Wireless Magnetic Sensors
- Wireless Inertial Sensors
- Marker based (Optical)
- Pure vision based (no markers):
  - First systems exist
  - High computational power needed (cluster)

Optical: Vicon

- 3 different camera models (0.3 – 4M pixels; 240-1000fps)
- Very high quality
- Price starts at 70K

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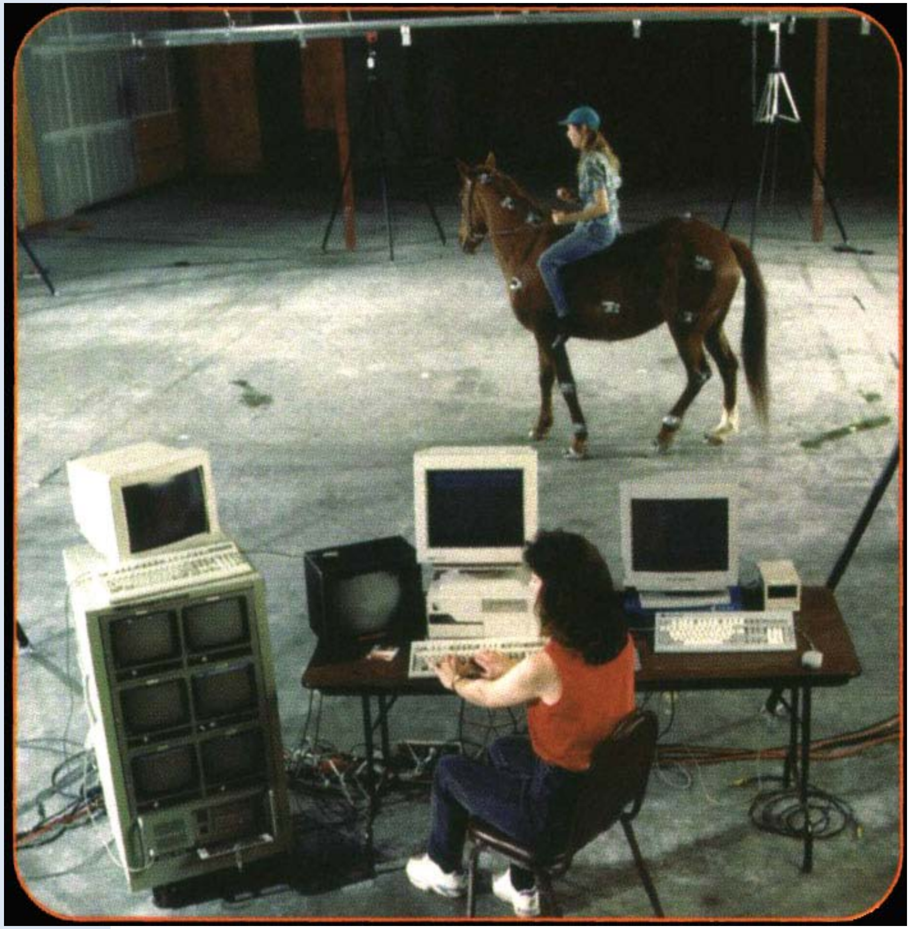
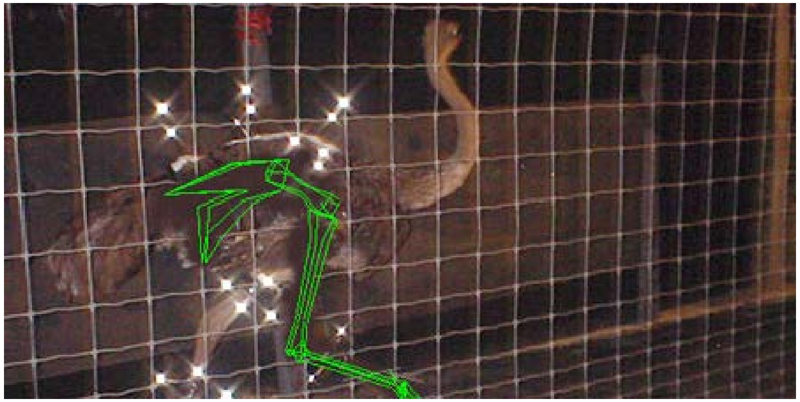
Tracking Animals

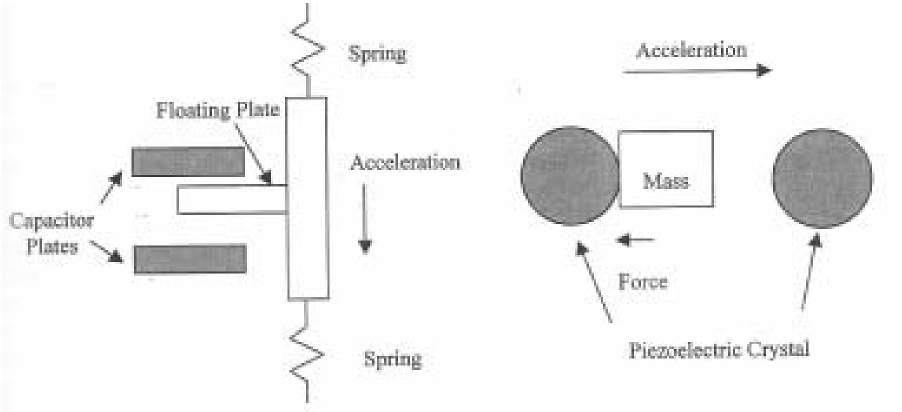




Inertial Sensing

Inertial or Gravimetric

- Accelerometers
  - Linear accelerations
  - Mass on spring in tube; Piezoelectric
- Rate sensors (Gyroscope)
  - Angular velocity
  - Excentric mass….
- Gravity sensors
  - Orientation in gravity field



(Explanation: Piezoelectricity is the ability of certain crystals to generate a voltage in response to applied mechanical stress.)

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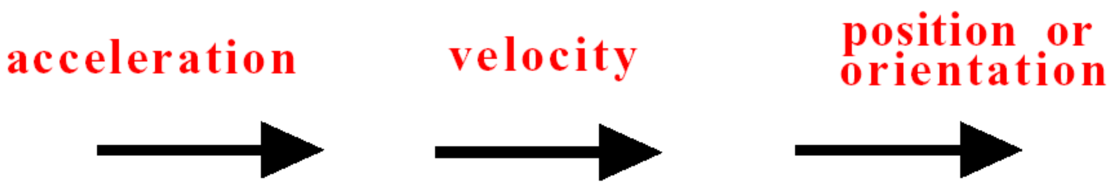
Inertial Navigation

- Relative navigation from known starting point
- Sense rate, integrate once
- Sense Acceleration, integrate twice



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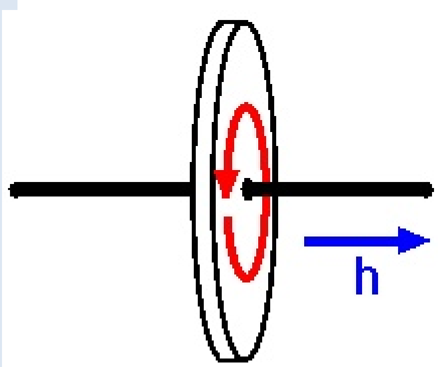
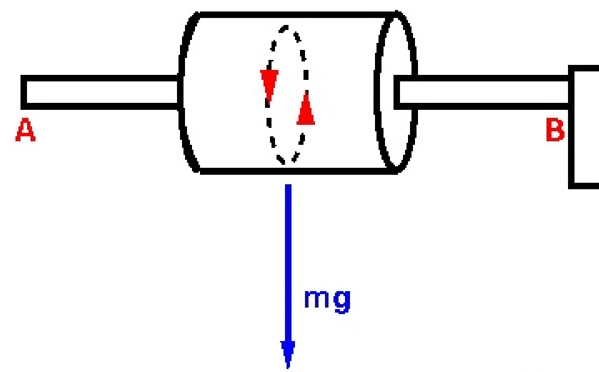
How to Measure Angles with a Gyroscope?





„Drehimpulserhaltungssatz“

For any collection of spinning objects, the total angular momentum must stay constant.

Vibrating Gyroscope

- When rotated a **vibrating element** (vibrating resonator) is subjected to Corioli's effect.
- Coriolis effect causes secondary vibration orthogonal to the original vibrating direction
- Sensing the secondary vibration -> the rate of turn can be detected
- For vibration exert and detection the piezo-electric effect is often used -> often called "piezo", "ceramic", or "quartz" gyro

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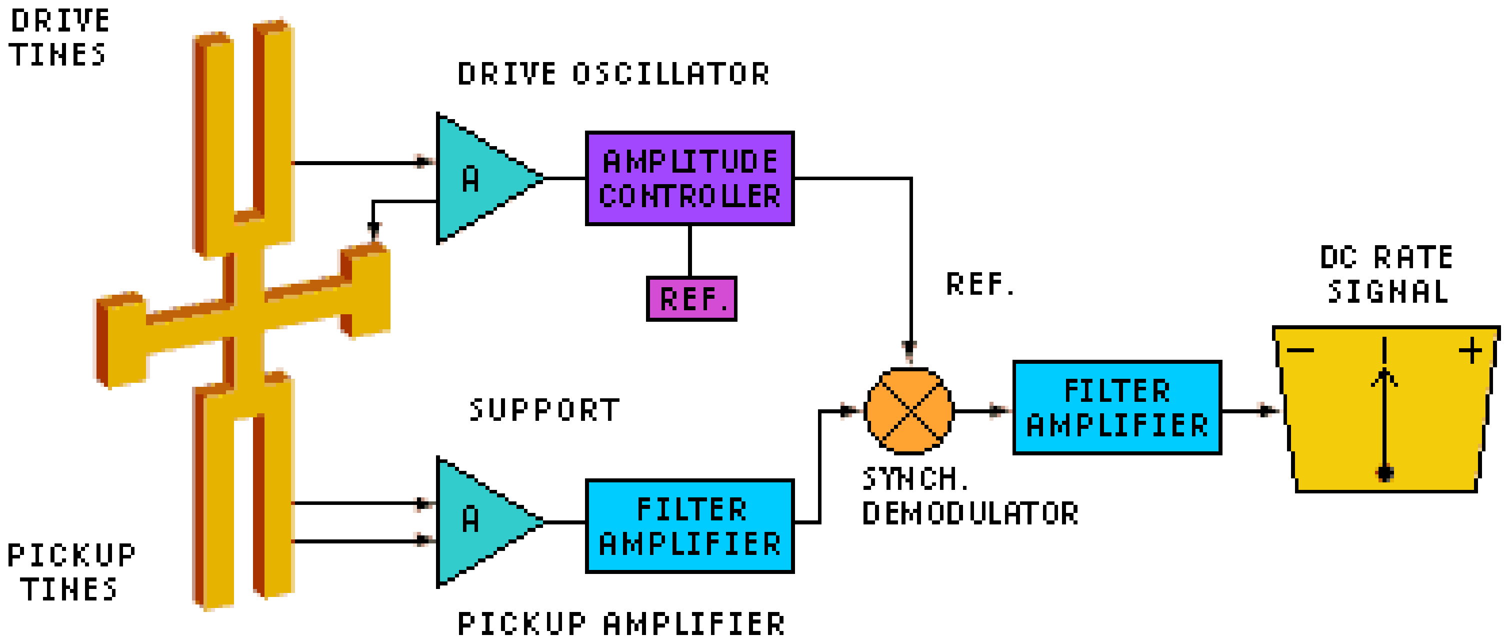
The GyroChip™



Quartz tuning fork -> rotation -> coriolis force-> voltage

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Vibrating Gyro

- suitable for mass production and almost free of maintenance
- Drawback
  - If used under external vibration, it cannot distinguish between secondary vibration and external vibration
  - can be partly overcome by using other vibrating elements (rings) instead of tuning fork

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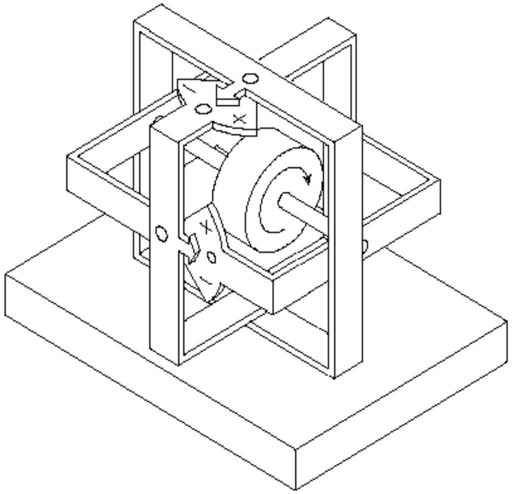
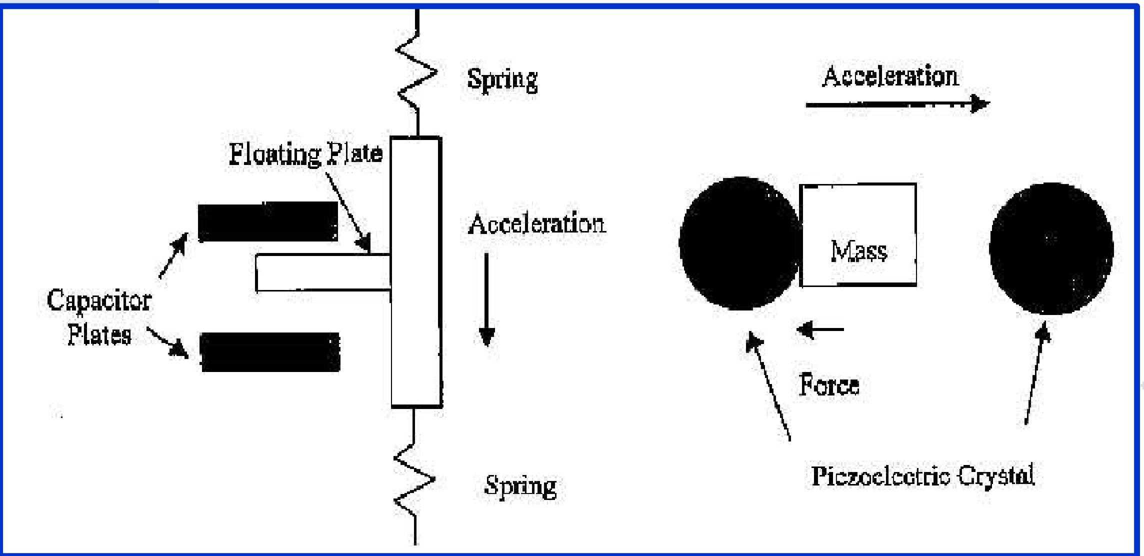
Inertial Trackers



- Intersense IS-300
- Less noise, lag
- Mostly only 3 DOFs (orientation)
- Relative measurements
  --> integration errors --> drift

Types:
Gyroscopes
Accelerometers
Inclinometer
Electronic compass



Application Areas

- Stabilization
  - Satellite Communication Antennas
  - Optical Line-of-Sight Systems
  - Missile Seekers
  - Electro-Optical Infared Radar Systems
- Controls
  - Aircraft & Missile Flight Control
  - Attitude Control
  - Yaw Dampers
- Guidance
  - Missile Mid-Course Guidance
  - Inertial/GPS Navigation Systems
- Instrumentation
  - Sounding Rockets & Missiles
  - Simulation & Training Aids

MotionPak 2™

6 DOF

Size ~ 6x6 cm

X-UFO

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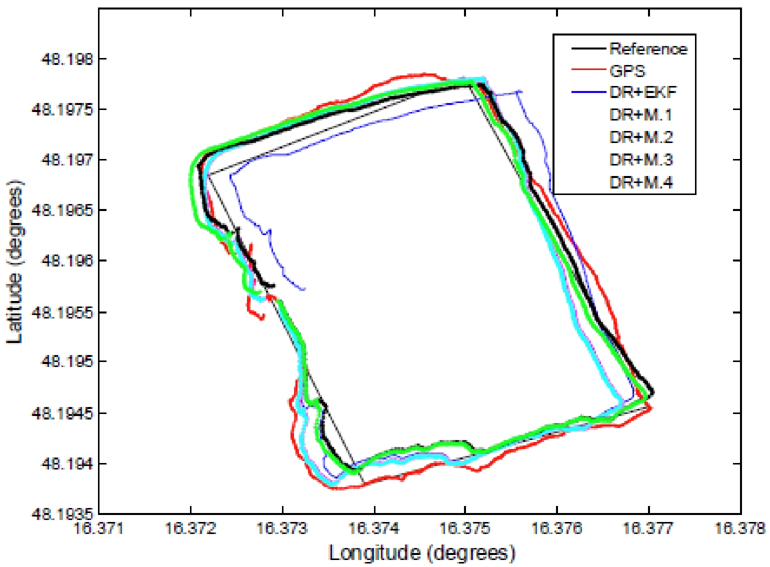
Navigation of Humans/Machines

- Traditionally used in robotics (inertial and/or optical)
- Outdoors additionally GPS



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Motion Capture with Inertial Sensors

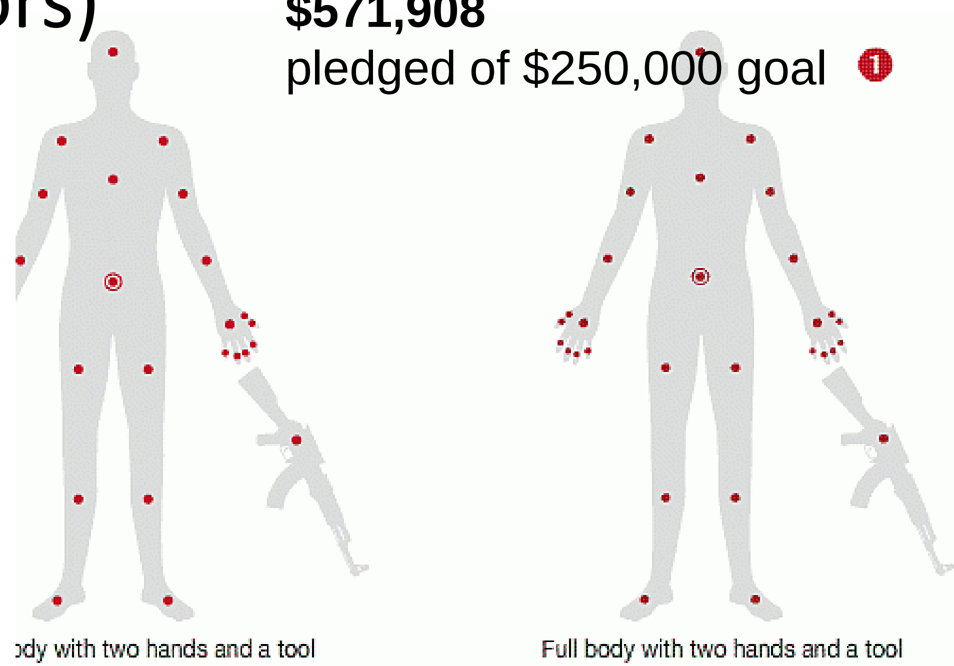
X-sense MVN

PrioVR

Inertial MoCap: Perception Neuron

- Low cost: 1.500 EUR
- 32 sensors – flexible use
- USB or WiFi transfer
- 60 fps (with 32 sensors)
- Finger Tracking

Kickstarter 2015:
$571,908
pledged of $250,000 goal



Inertial Tracking - Sensors

- Pros
  - Truly Sourceless
  - Very fast
  - Robust
- Cons
  - Bias, scale and alignment errors
  - Bias integration results in drift
  - Wireless versions require “bigger” sender

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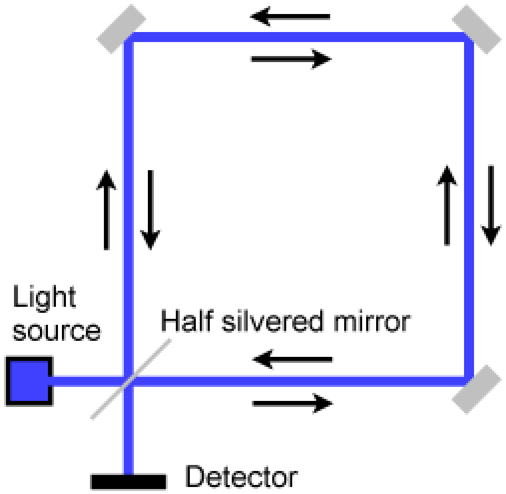
Other Gyroscopes & Additional Sensors



- Sagnac Effect
  - Ring Laser Gyroscope
  - Fiber Optic Gyroscope
- Quantum Gyroscope
- Electronic compass:
  Measuring the earth's magnetic field
- Inclinometer – measures slope (viscous fluid)

Time-of-Flight and Frequency Measuring

- Acoustic Trackers (Ultrasound)
- GPS / DGPS
- Radio Frequency
  - WLAN
  - RFID
  - UWB
  - …

Time-of-Flight and Frequency Measuring

- Measure the time of propagation of a signal
- Compare phase difference of waves
- Measure frequency of waves to indirectly estimate time difference

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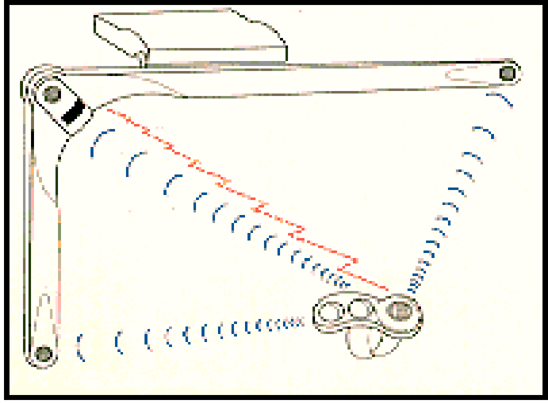
Acoustic Tracking



- Measure distance between reference features and moving target
- Determine distance: Measure time of propagation of pulsed signals (travel time of sound)
  - Speed of propagation must be constant (!)
- Pulsed signal: Ultrasound (~40Khz)
- Use 3 or more emitters and 3 or more recievers (6 DOF)
- Typical setup for 3 DOF:
  - 3 microphones, 1 speaker

Logitech Fly Mouse

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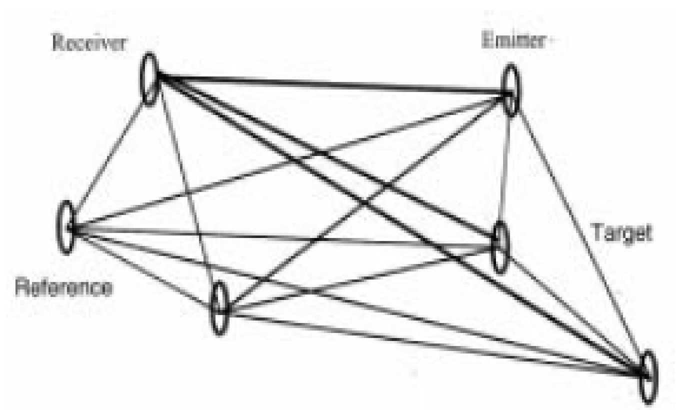
Ultrasonic Time-of-Flight

- Each emitter sends out signals sequentially
- Recievers recieve signals simultaneously
- Compute position of target emitters with respect to the fixed reference via simple triangulation
- Repeat for (at least) 3 target emitters

  → position and orientation of target with respect to fixed reference



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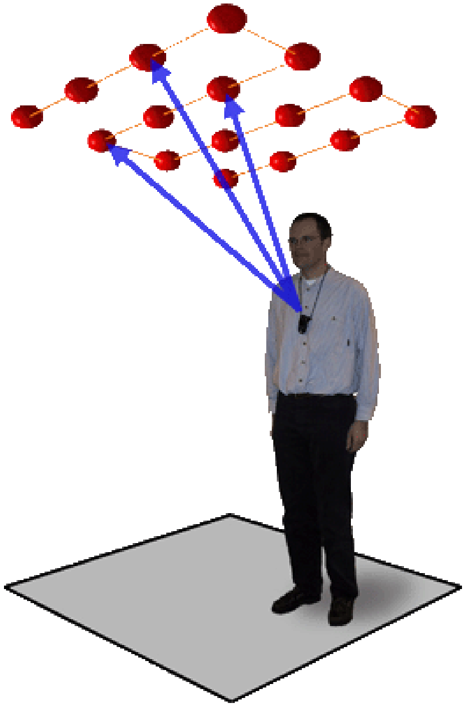
Acoustic Tracking: Pros & Cons

- Advantages
  - Small and light weight targets
  - Relatively inexpensive
- Disadvantages
  - Line of sight issues
  - Accuracy depends on constancy of velocity of sound
  - Speed of ultrasonic waves varies
    - Temperature, Pressure, Humidity, Turbulence
  - Ultrasonic noise
    - CRT tubes of monitors, disk drives, etc.
    - Reflection of signal

Acoustic Trackers: Wide Area

- Wireless targets are possible
- Example: AT&T Cambridge BAT, IS-900

AT&T Bat

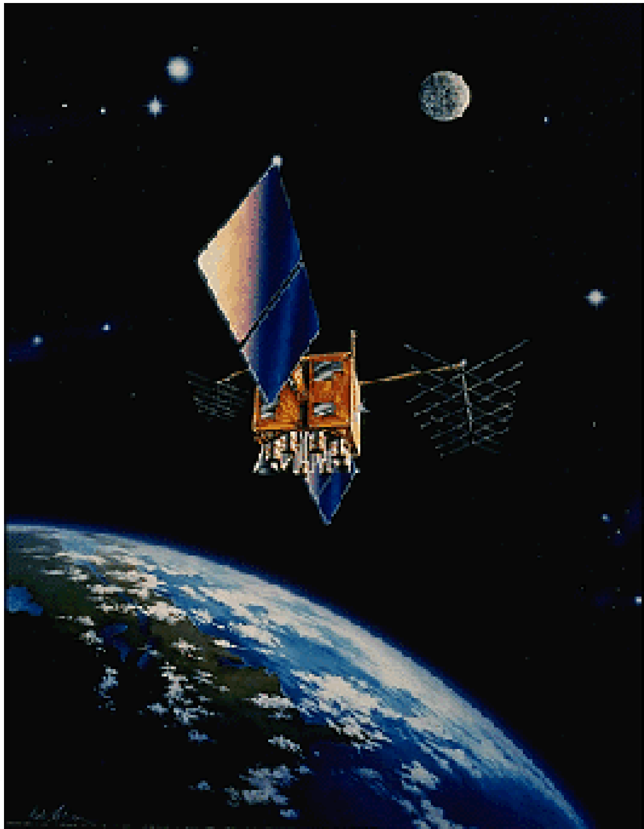


Global Positioning Systems (GPS)

Global Navigation Satellite Systems (GNSS)

- GPS (USA; Global Positioning System)
- GLONASS (Russia)

  “Globalnaja Nawigazionnaja Sputnikowaja Sistema”
- Gallileo (Europe)



GPS

- Large scale
- Based on radio signals
- Uses 24 satellites in orbit -> 4 of them seen simultaneously from any point on earth
- + 6 monitoring stations, 4 ground antennas, 1 master control station

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GPS

- Two levels of service:
  - Standard positioning service (SPS)
  - Precise positioning service (PPS) -> only for U.S. Government
- Each satellite has atomic clock (accuracy 340ns for SPS)
  - 1ms clock error produces horizontal measurement error of 300km
- Master control station controls orbit of satellites and corrects clocks

GPS Receiver

- Receiver needs to receive signals from at least 3 different satellites to determine position
- BUT receives clock as unknown time bias! (drift)
- Satellites more accurate (2ns/year) than GPS receivers (10ns/day)
- Therefore use 4 satellite signals to calculate position and time bias; in practice: 5 satellites!!
- Accuracy of SPS: 100m
- Accuracy of PPS: at least 10x better than SPS

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GPS Pros & Cons

- Advantages:
  - Uniform global accuracy (~ 10-100m) without other infrastructure
  - Cheap and easy to use
- Disadvantages:
  - Direct line of sight needed - no GPS data indoors
  - Problems in narrow street passages, wood,…
  - Resolution and precision

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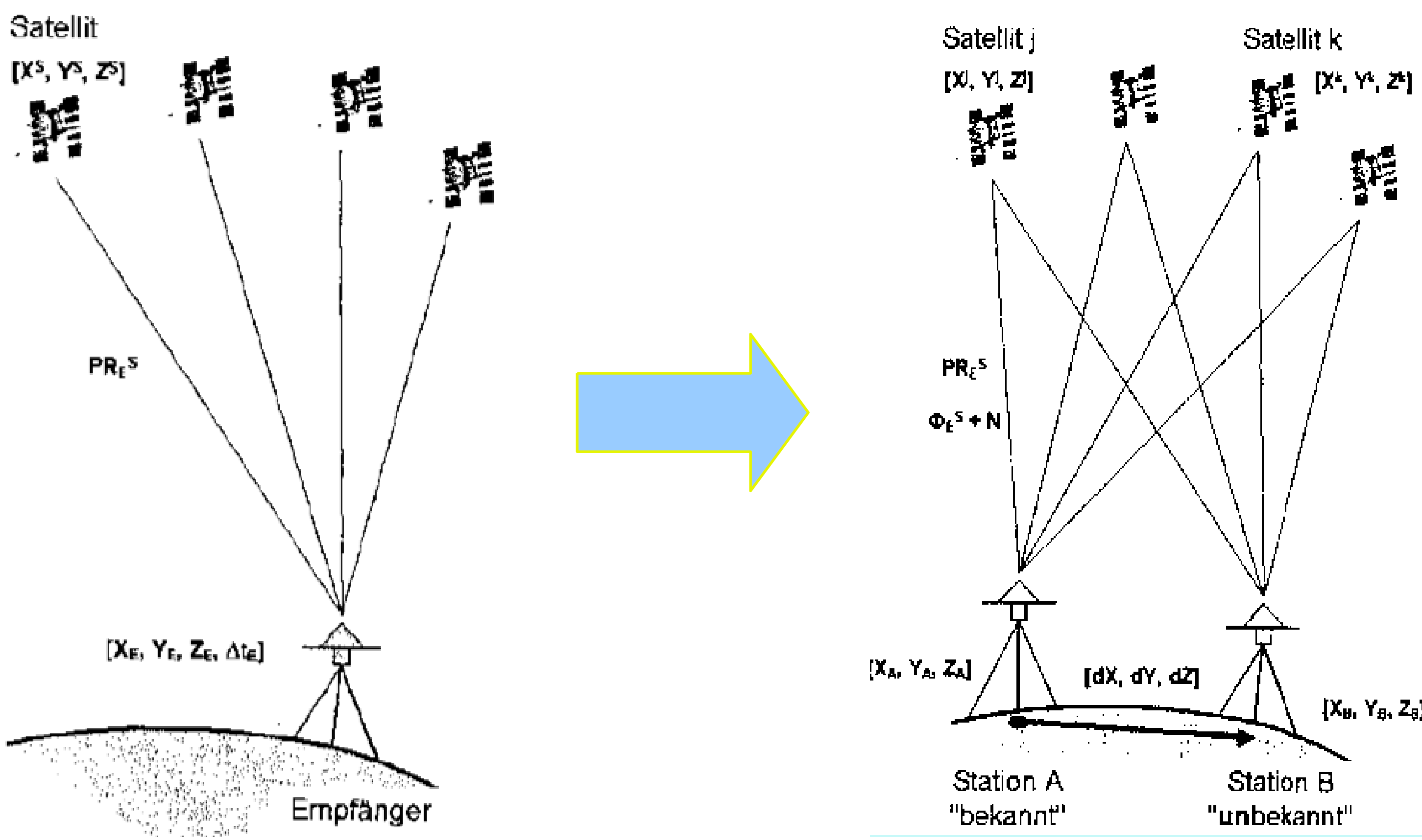
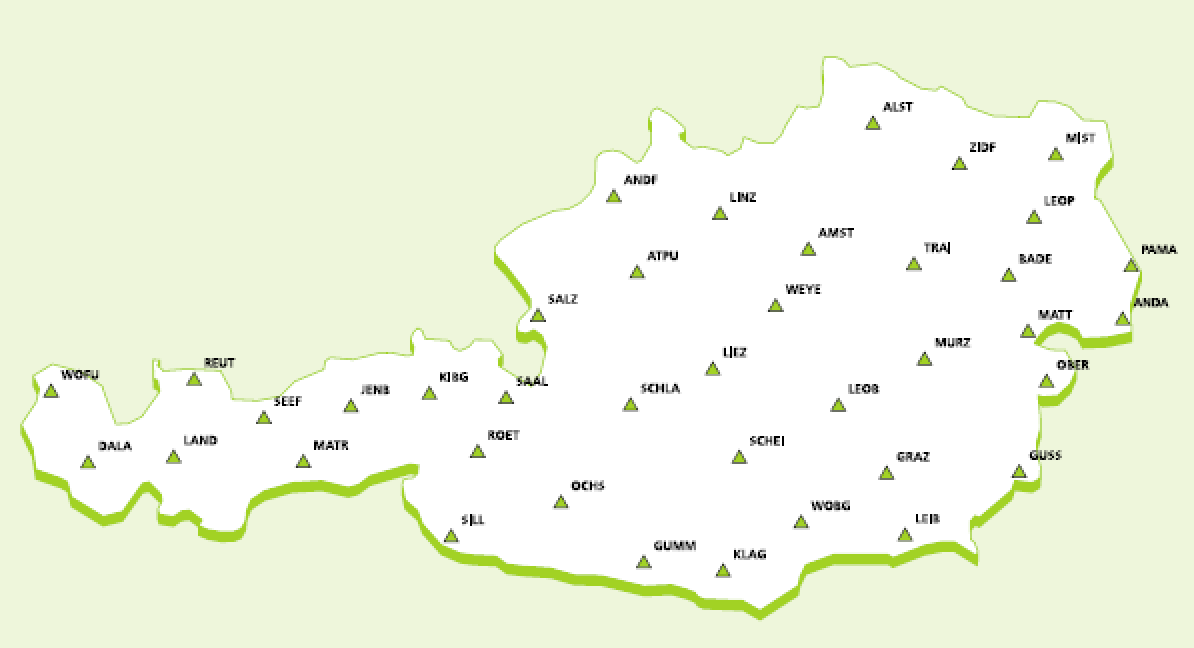
Differential GPS (DGPS)

- Uses additional fixed ground station to refine resolution
  - Theoretically 0.1m, practically 3-5m



Austrian EPOSA System

- Differential correction data sent over GMS, Internet (by RTCM or NTRIP standard)
- Supports GPS and GLONASS
- Cooperation between BEWAG, ÖBB-IKT and Wien Energie
- 1-3 cm Precision



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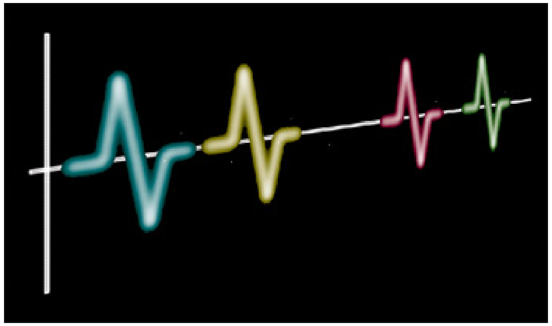
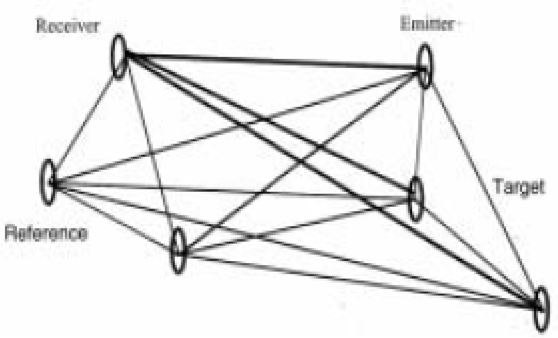
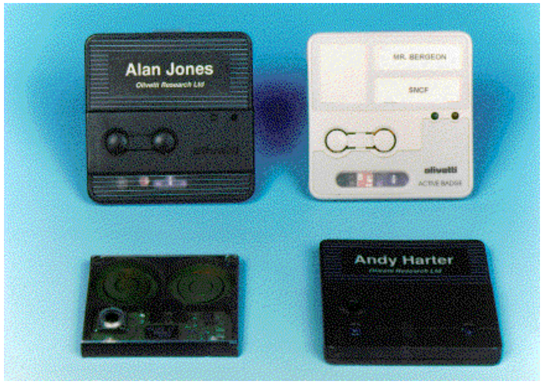
Radio Frequency Trackers



- Triangulation similar to acoustic tracking
  - Proximity
    - 802.11a/b = WLAN
    - RFID
    - GSM
    - Ultra Wideband
  - Phase difference





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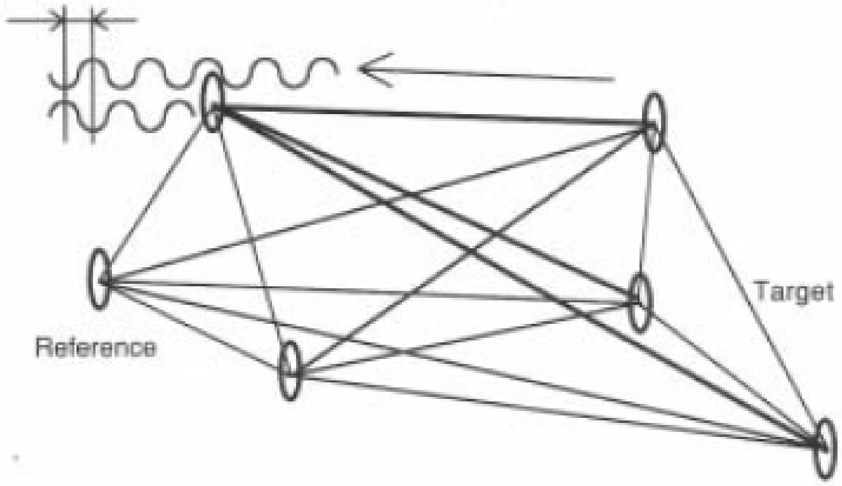
Phase Difference Time of Flight

- Similar to acoustic tracking
- Target sends signal
- Receiver has reference signal with the same frequency
- Receiver compares phase shift of target signal with reference
- Modification of phase indicates relative movement of target
- Example: laser measuring



Phase Shift Pro & Cons

- Advantages
  - High data rates possible (phase shift can be measured continuously)
- Disadvantages
  - Limited to environmental conditions
    - Temperature, pressure, ….
    - GPS: Ionospheric influences (sun winds)
  - **Reflections** in the environment are problematic
    - Multipath effect
  - Accuracy
  - Cumulative errors in measurement process

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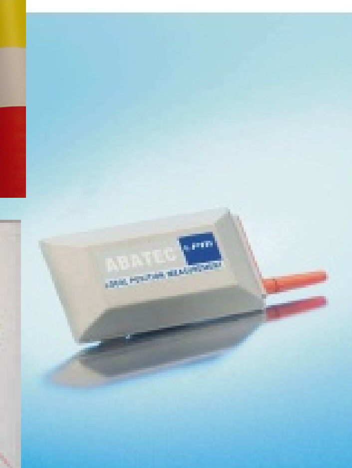
Ubisense Ultrawide-band (UWB)

- UWB transmits signal over multiple bands of frequencies simultaneously: 3.1 - 10.6 GHz (RFID systems operate on single bands of radio spectrum)
- Active tags used; Ubisensors 5.8 to 7.2 GHz
- Tags have unique 32-bit (4-byte) identifier and send location max. 40 Hz

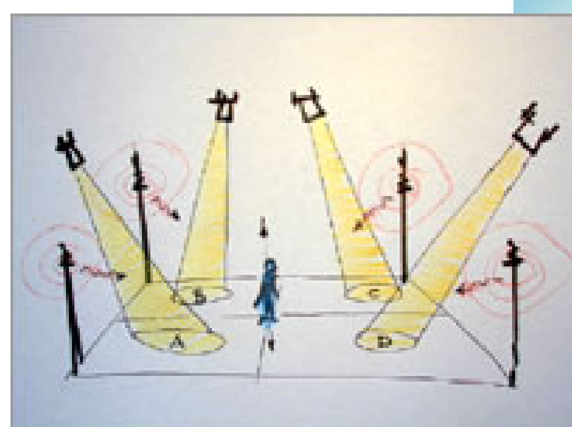
Inmotio: Local Position Measurement (LPM)

- Austrian company: Inmotiotec
- Large area tracking
  - Red Bull Air Race
  - Zactrack
- 500x500m area/sect.
- Max. 30 sections
- Like UWB: 5.8Ghz
- Update rate: 1000Hz
- Accuracy: +/- 5cm (outdoors)

Base station



Transponder



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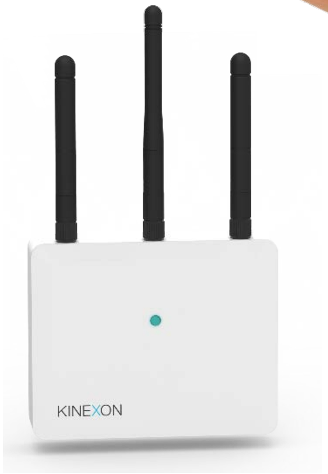
Kinexion – Decawave

- Decawave IEEE 802.15.4 standard
- UWB: over 15 diff. frequency bands
- +/- 10cm accuracy
- Inertial sensor integrated
  - <0.1° orientation data & acceleration
- 40m indoors, 300m outdoors
- 15g sensors
- Industrial & sports applications



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Hybrid Trackers

- Idea: one tracker's strength is other tracker's weakness
- For example: Intersense IS-600 / 900
  - inertial: +fast, -drift
  - acoustic: -slow, +accurate

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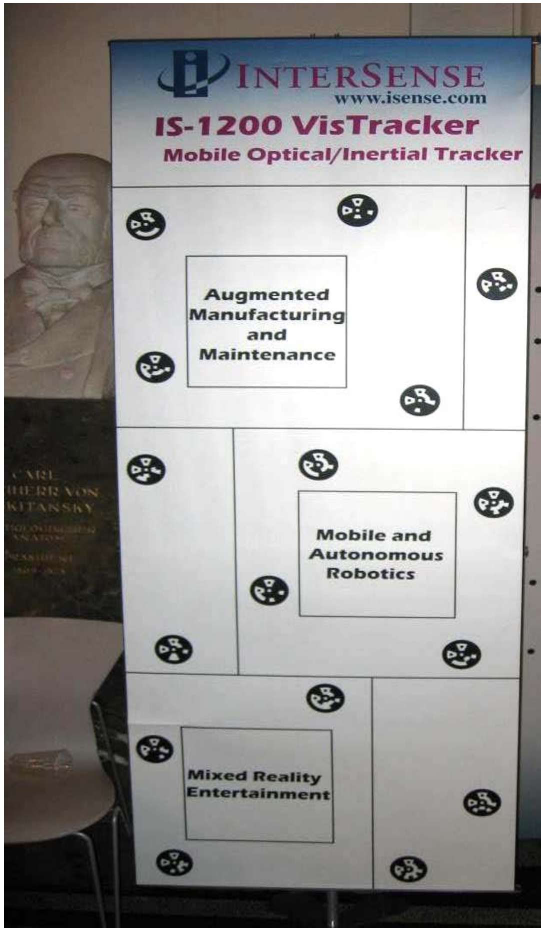
Intersense IS-1200

- Combination of inertial + optical tracking
- Advantage: Very accurate
- Disadv.: Markers needed



Miscellaneous Devices

- Gloves
- Pens / Wands
- Hybrid Devices
- Game Controllers

- Haptics
- Locomotion

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Data Gloves

- Used to track the user's finger movements
  - for gesture and posture communication
- Almost always used with a tracker sensor mounted on the wrist
- Common types
  - CyberGlove
    - 18 sensors, 22 sensors
  - 5DT Glove
    - 5 sensors, 16 sensors
  - P5 Glove
    - bending sensors

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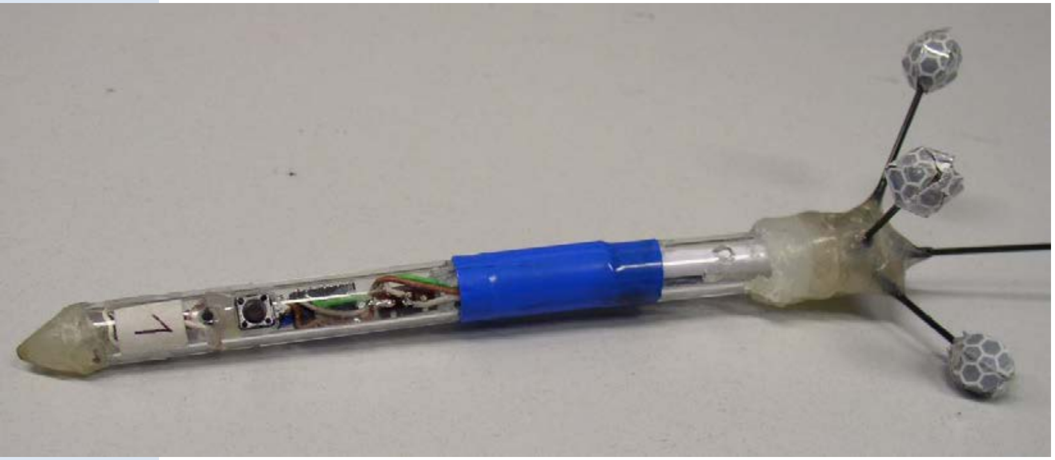
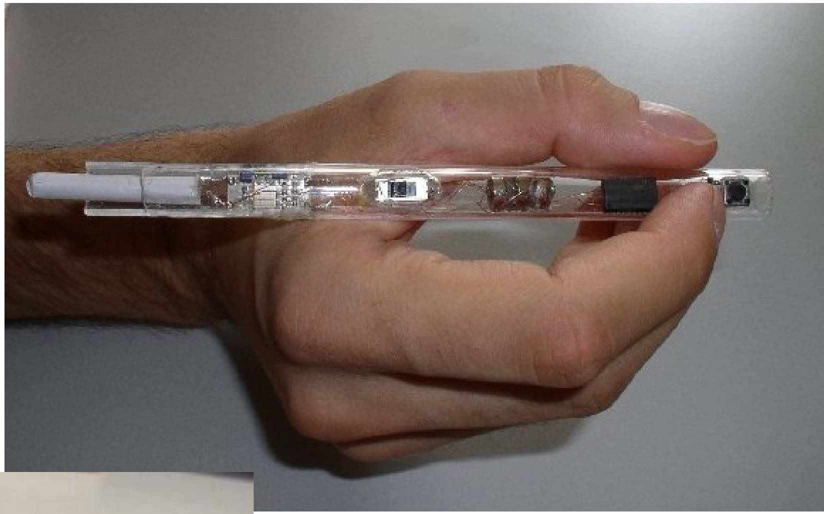
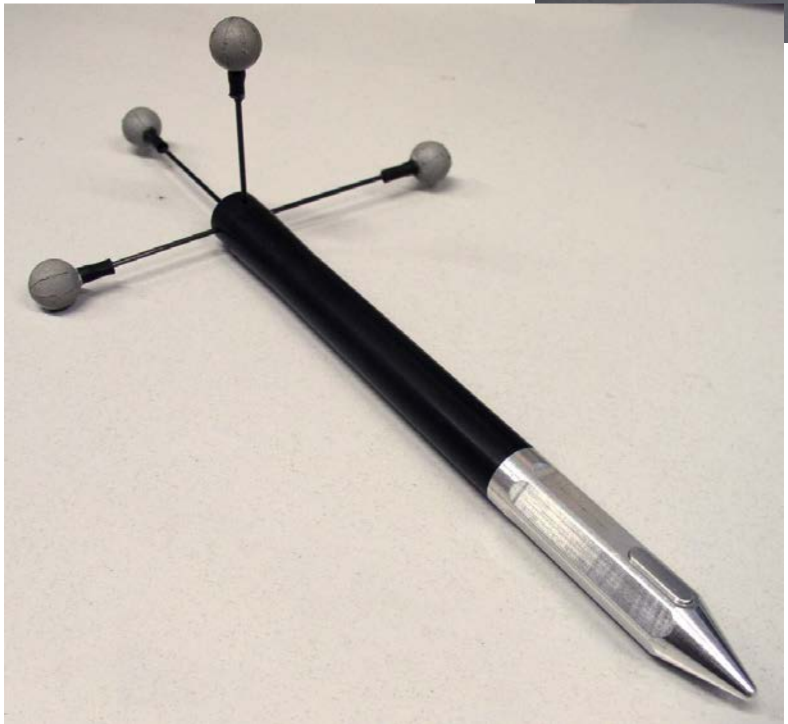
Tracked Wireless Pens (IMS)







Hybrid devices

Continuous and discrete input

Examples

- Button device + tracker
- Flex & Pinch
- Ring mouse
- LCD tablet
- Shape Tape
- Cubic Mouse
- Spaceball

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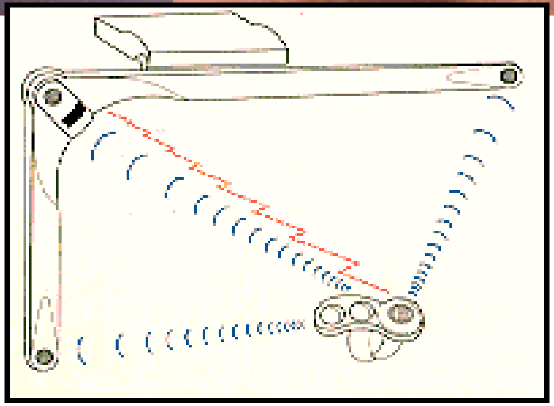
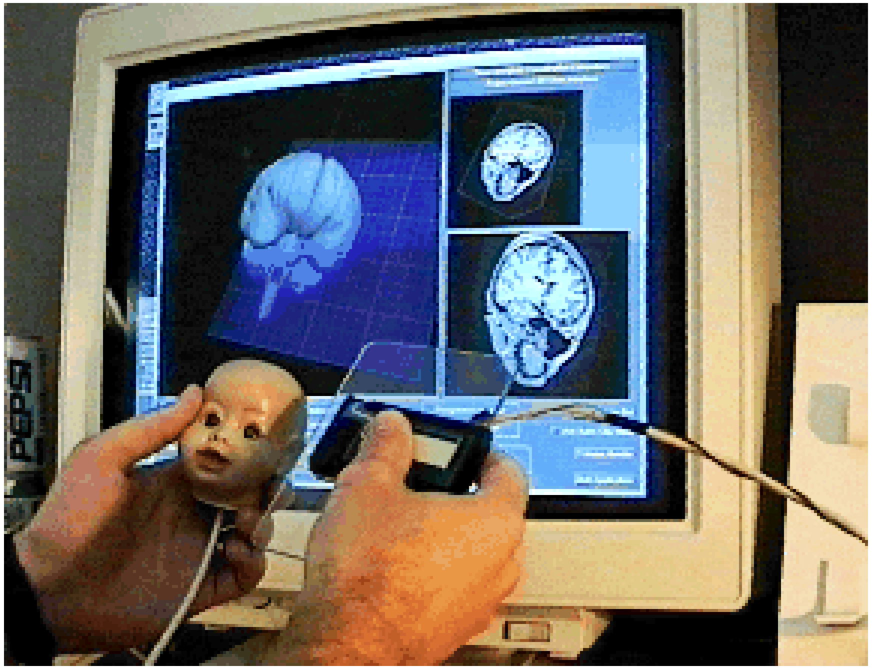
Mouse Type Devices

- Space Mouse
- Ring Mouse (pictured)
- Fly Mouse
- Gyro Mouse



Various Props – Real Objects

- Head prop
- Car prop
- ...



Brain segmentation

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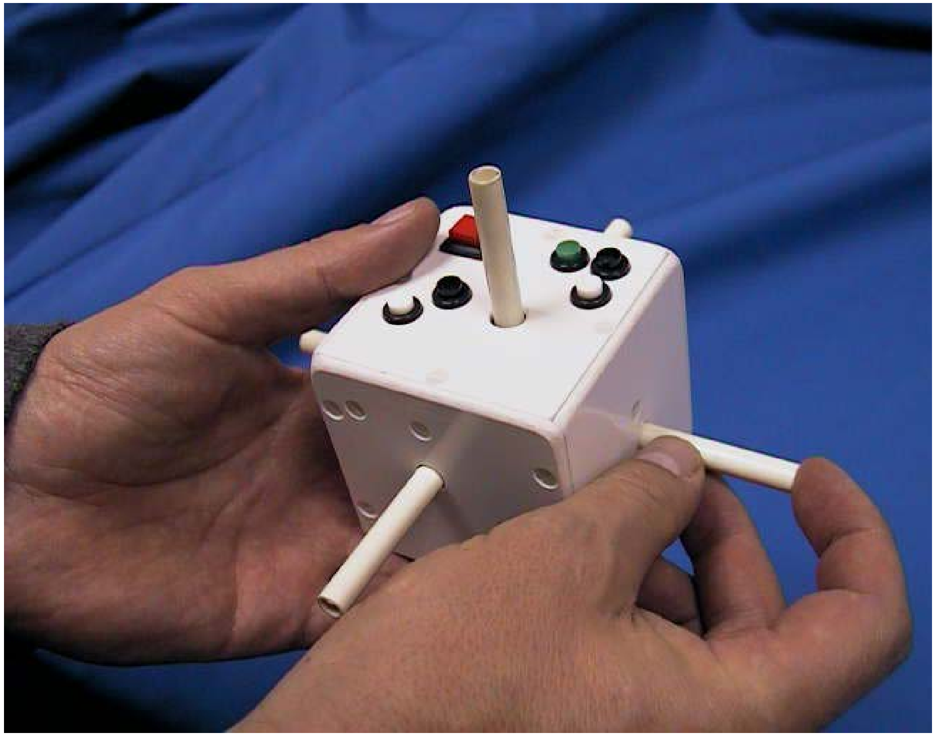
Cubic Mouse

- First 12 DOF input device
- Tracks position and rotation of rods using potentiometers

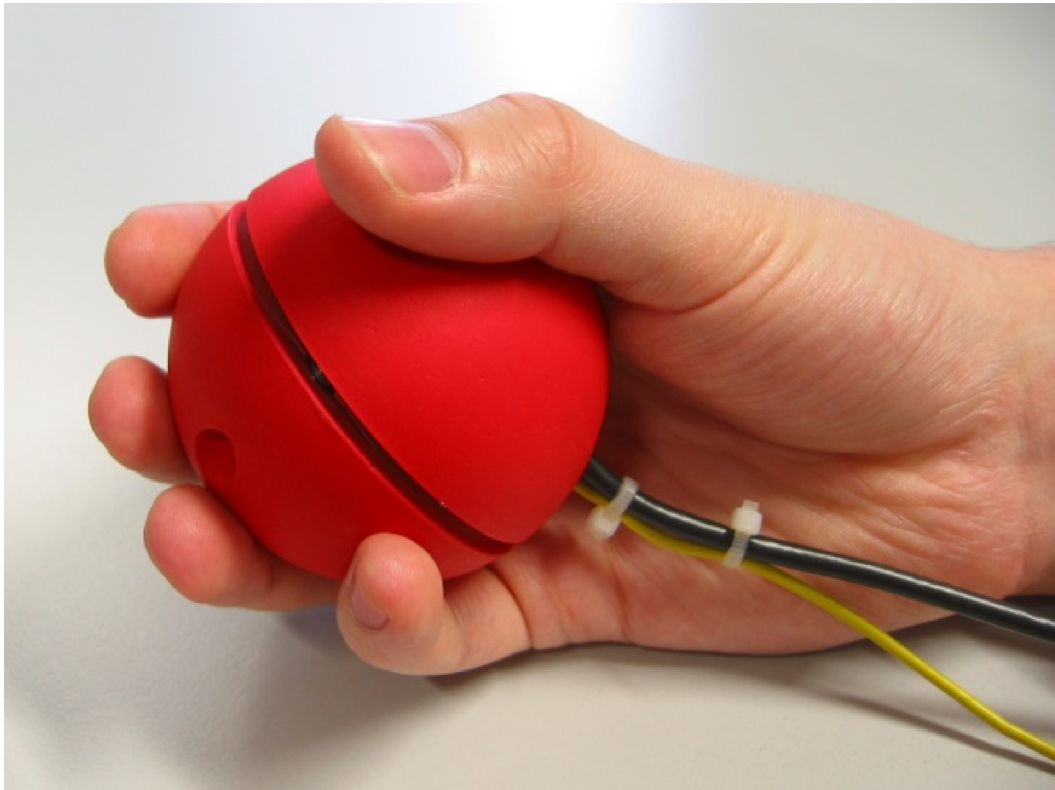


- Other shapes and implementations possible
  - Mini Cubic Mouse
  - …

iOrb

- Inertial Tracker inside
- 1 Button
- Freely rotatable

Reitmayr et al., 2004



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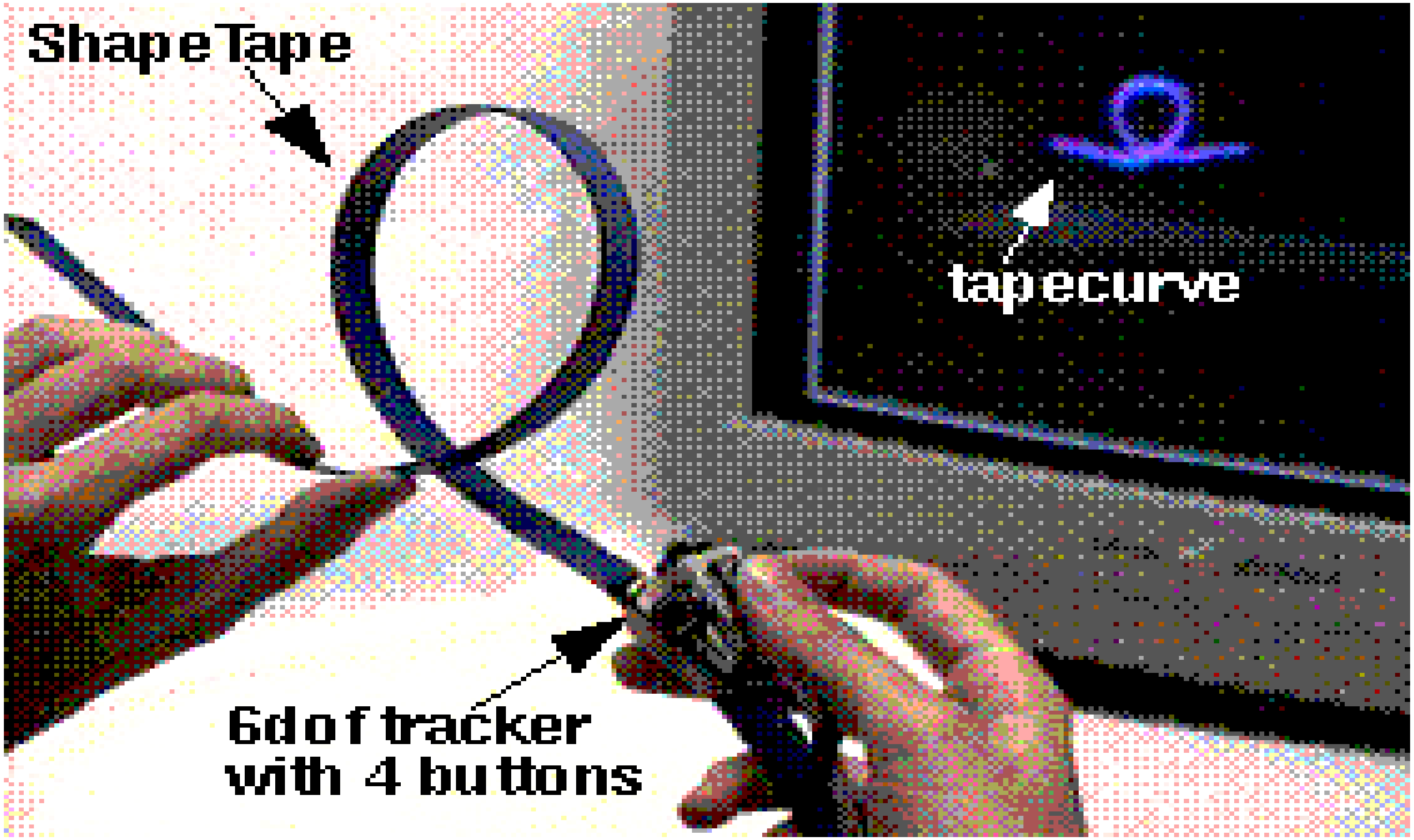
Shape Tape



Courtesy Balakrishnan et al

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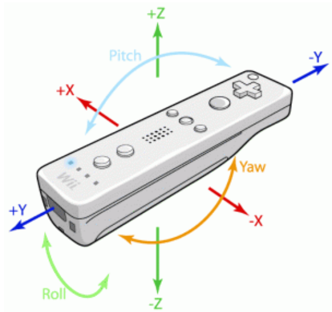
Wiimote



- 3-axis accelerometer
- Optical (IR) sensor
  - IR LEDs on a sensor bar used for recalibration
  - Calc. distance to sensor bar
  - max. 5 points simultaneously
- Rumble functionality

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Sony MOVE Motion Controller

- Inertial sensor (gyro, accel., magnetom.) – measures orientation
- 60 Hz camera used for optical tracking of colored sphere
  - High accuracy (cm/mm)
  - Controller can change colors (eases segmentation)

Haptic Devices

Tactile Technologies – Feeling Pressure

- Tactile information is produced by perturbing the skin
  - Pins -either alone or in an array, as in devices for Braille display
    - typically used for fingertip stimulation
  - Air jets blow to produce a disturbance
  - Cushions of air can be inflated or deflated to vary pressure on skin
  - Electrical stimulation -low levels of current provide a localised tingling sensation
- Typically used in gloves, or for larger body areas
- These technologies all share the same lack of realism

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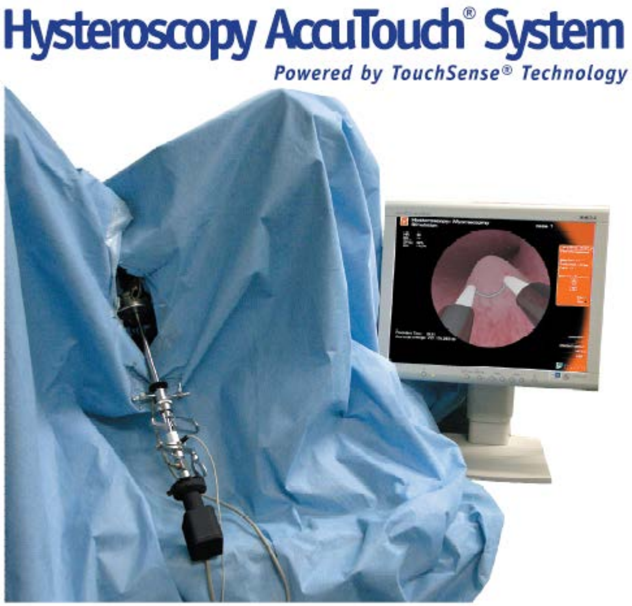
Haptics

- Human tactile sensoring sensitive to vibration 10-1000Hz -> 1000Hz required for stable force feedback
- Physical accuracy difficult to achieve in real time
- Simplified/approximate (deformation) models
- GPU based haptics modelling approaches

- Haptics devices & photos: http://www.personal.rdg.ac.uk/~shshawin/LN/L8hapticdesigns.html
- Futher literature: Good introduction to haptics: http://www.dcs.gla.ac.uk/~stephen/lectures/HCI4/HCI4%20kinaesthetic%20haptics.pdf

Haptics – Special Devices

- Haptic Smarttool
  - Could be useful for medical applications
- Medical Training Devices (e.g. Endoscopy)



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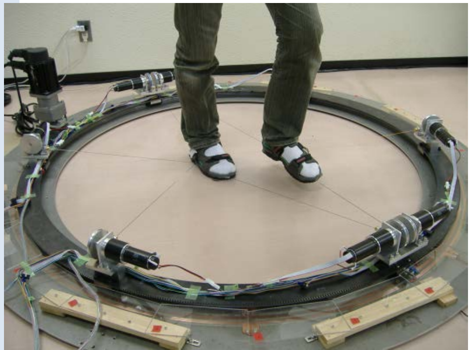
Locomotion devices

Locomotion = Active Movement

- Treadmills
- Stationary bicycles
- Walking/flying simulations (use trackers)

Locomotion - Prof. Iwata

- Virtual Preampulator (1996)
- TorusTreadmill (1999)
- GaitMaster 2 (2000)
- CirculaFloor (2005)
- Powered Shoes (2006)
- StringWalker (2007)



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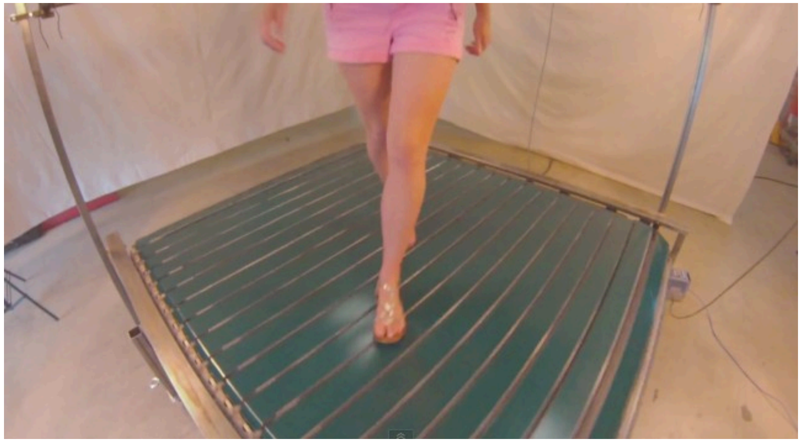
Current Locomotion Devices (2014 -)

- Cyberith Virtualizer
  - Developed by Tuncay Cakmak (TU Vienna)

- Infinadeck Omni-Directional Treadmill (ODT)
- Virtuix Omni



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Literature

- 3D User Interfaces – Theory and Practice (2nd ed.) J. LaViola, Ernst Kruijff, Ryan P. McMahan, Doug Bowman, Ivan Poupyrev; Addison Wesley, 2017.