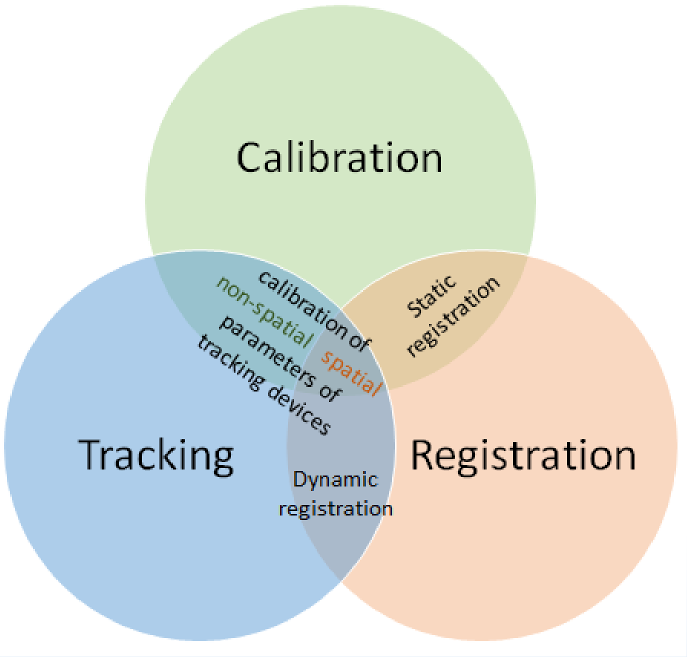
Tracking

Tracking

- Tracking
  - ➢ Dynamic determination of spatial properties at runtime
  - ➢ Tracking in AR/VR is always in 3D
    - Sensing and measuring in real time
  - ➢ Continuous measurement of position and orientation
    - For example
      - A user's head, eyes, limbs
      - In AR, an object or a marker
  - ➢ Tracking, registration and calibration
    - Terms associated with the measurement and alignment of objects
    - Overlap in practice

Tracking

- Registration
  - ➢ Alignment of spatial properties
  - ➢ In AR, registered objects aligned to each other in a coordinate system
  - ➢ Goal
    - Accurate registration of virtual information with physical objects
  - ➢ Static registration
    - When the user/camera is not moving
    - Requires calibration of tracking system
  - ➢ Dynamic registration
    - When user/camera is moving
    - Requires tracking

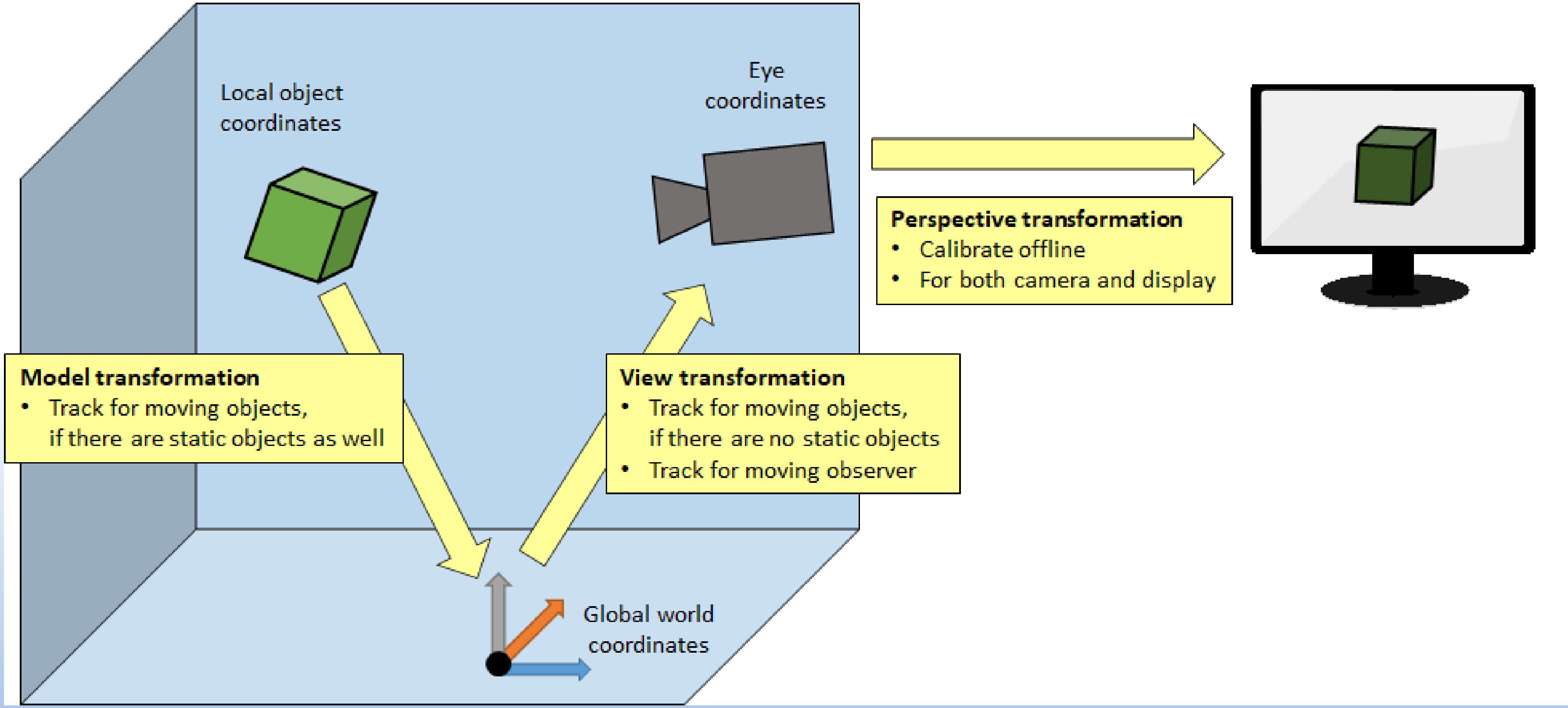


Tracking

- Tracking
  - ➢ Dynamic sensing and measuring, continuous
  - ➢ Must know the relative pose
    - Position and orientation
- Calibration
  - ➢ Correlates sensor readings with a standard or a reference sensor
    - Device to be calibrated to a known scale
    - Check and adjust a sensor's accuracy
  - ➢ Usually only performed at discrete times
    - Once for the lifetime of the device (during manufacturing)
    - Before commencing an operation
    - Autocalibration – concurrently with tracking

Coordinate Systems

- Coordinate systems
  - AR relies on the standard computer graphics pipeline to produce overlays on the real world



Coordinate Systems

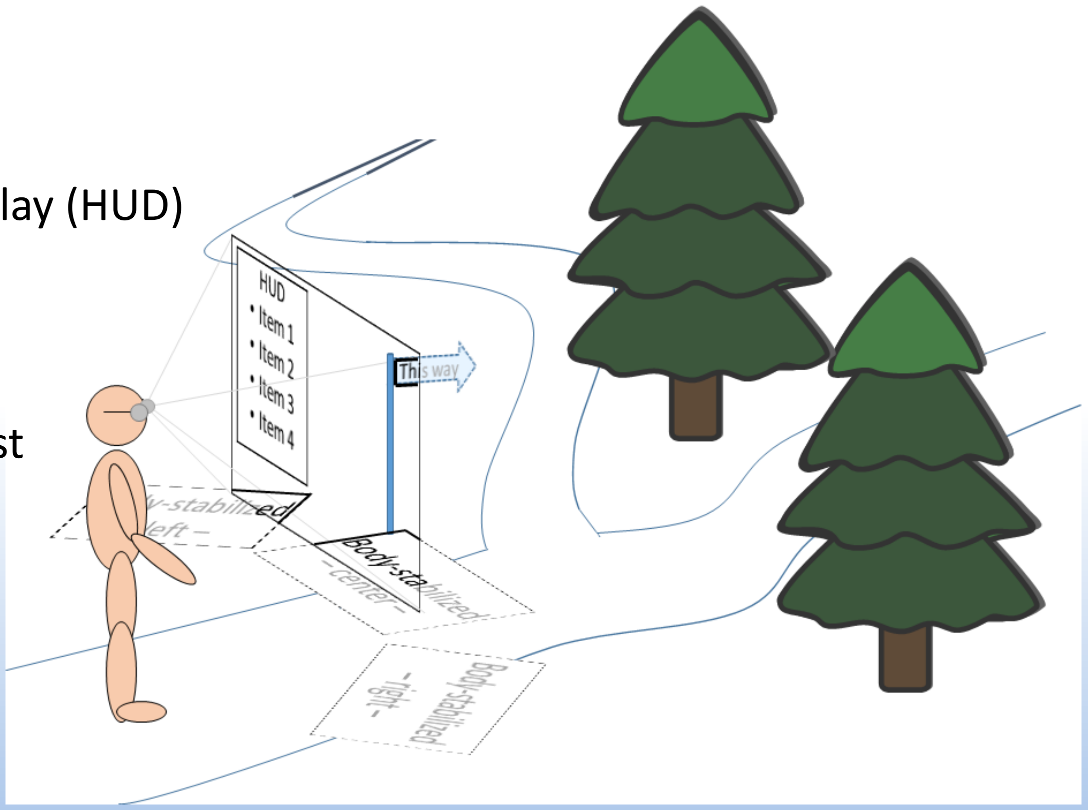
- Model transformation
  - ➢ Relationship of local 3D object coordinates with global coordinates
    - Determines where objects are placed
  - ➢ Virtual objects
    - Controlled by the application and do not require tracking
  - ➢ Real objects
    - Static
      - – Do not require model transformation
    - Dynamic
      - – Register virtual information and track model transformation

Coordinate Systems

- View transformation
  - Relationship of 3D global coordinates with camera coordinates
    - Important if the user is allowed to move
    - Some video see-through devices may require calibration of camera and display
- Projective transformation
  - Relationship of 3D camera coordinates and 2D device coordinates
    - Content of the view frustum projected onto the screen
  - Calibrated offline for each camera and display

Frames of Reference

- In AR, virtual information
  - Fixed with respect to the global world, an object, or a person's view (AR screen)
  - Screen-stabilized
    - Fixed to the display
      - E.g., heads-up display (HUD)
  - World-stabilized
    - Fixed to the world
      - E.g., virtual signpost
  - Body-stabilized
    - Move with the user
      - E.g., virtual panels



Characteristics of Tracking Technology

- Measurement coordinates
  - ➢ Global vs. local measurements
    - Global
      - – Larger (or unlimited) workspace
      - – More freedom of movement
    - Local
      - – Smaller scale, better accuracy and precision
  - ➢ Absolute vs. relative measurements
    - Absolute
      - – Coordinate system defined in advance
    - Relative
      - – Reference coordinate system established dynamically
      - – Incremental sensing
        - » E.g., mouse movement based on the last measurement

Characteristics of Tracking Technology

- Physical phenomena
  - ➢ Electromagnetic radiation
    - Visible light
    - Infrared light
    - Laser light
    - Radio signals
    - Magnetic flux
  - ➢ Sound
  - ➢ Physical linkage
  - ➢ Gravity
  - ➢ Inertia

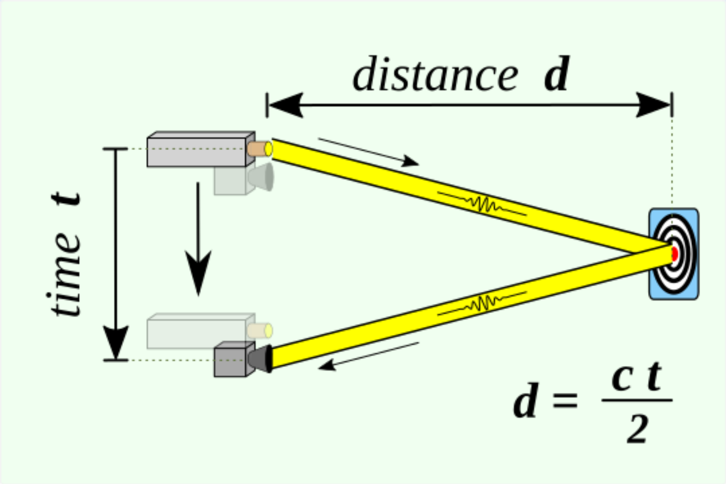
Greyson Orlando, Public domain, via Wikimedia Commons

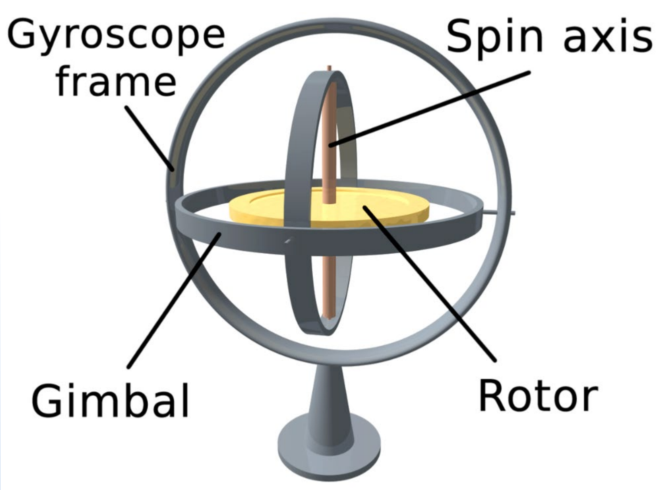
Characteristics of Tracking Technology

- Signal sources
  - ➢ Passive sources
    - Natural signals
      - E.g., natural light, earth magnetic field
  - ➢ Active sources
    - Requires electronic components to produce physical signal
      - E.g., acoustic, optical, radiowaves
    - Signal can be direct or indirect (reflected)
    - Most require open line of sight
  - ➢ No sources
    - E.g., inertia

Characteristics of Tracking Technology

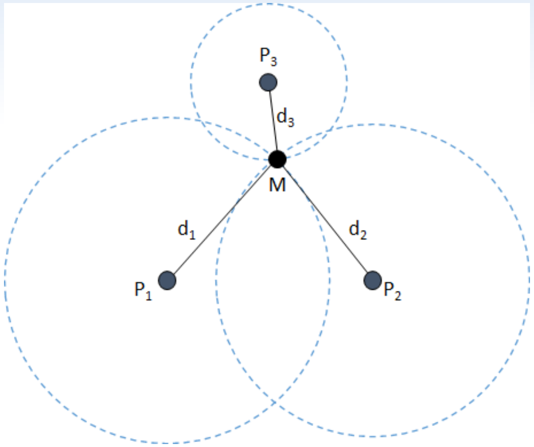
- Measurement principle
  - ➢ Signal strength
  - ➢ Signal direction
  - ➢ Time of flight
    - Absolute time
    - Signal phase
    - Requires synchronized clocks
  - ➢ Degrees of freedom (DOF)
    - Some sensors deliver only a subset
      - – E.g.
        - » Gyroscope: 3DOF, orientation only
        - » Tracked LED: 3DOF, position only
        - » Mouse: 2DOF position only

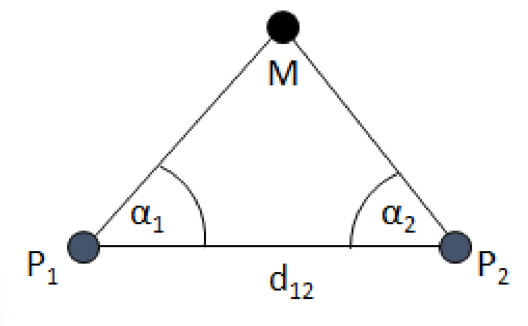




Characteristics of Tracking Technology

- Measured geometric property
  - ➢ Distances or angle
    - Trilateration
      - Geometric method of determining locations of points from at least three measurements
    - Triangulation
      - Determines locations of points from two or more measured angles
        - » At least one known distance
    - Can recover position and orientation of a rigid object
      - From position of three or more points





https://ar-tracking.com/en/product-program/targets

Characteristics of Tracking Technology

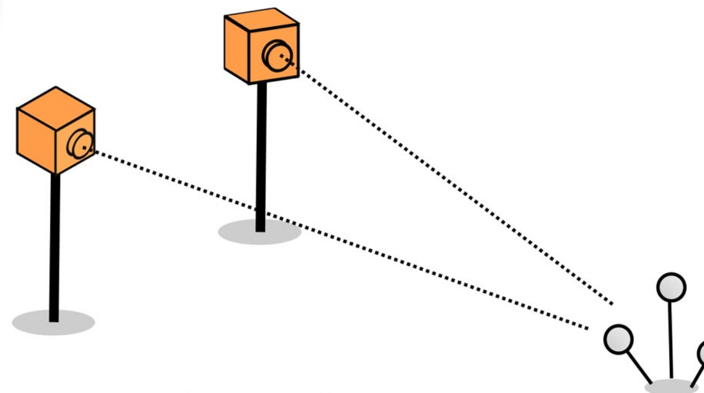
- Measurement error
  - Accuracy
    - How close measurement is to true value
    - Affected by systematic errors
      - Can be improved with better calibration
  - Precision
    - How closely multiple measurements agree with each other
      - Varies with type of sensor and DOF
    - Affected by random error and noise
      - Can be improved with filtering (more computation, more latency)
  - Resolution
    - Minimum difference that can be discriminated between two measurements
    - Theoretical property often unachievable in practice due to noise

Characteristics of Tracking Technology

- Temporal characteristics
  - ➢ Update rate
    - Temporal resolution
    - Number of measurements in a given time interval
  - ➢ Measurement latency
    - Time it takes from occurrence of physical event to data becoming available
  - ➢ End-to-end latency
    - Time it takes from occurrence of physical event to presentation of a stimulus
    - 60Hz display requires updates within a time interval of less than 17ms

Characteristics of Tracking Technology

- Sensor arrangement
  - ➢ Rigid geometric configuration
    - Common approach using multiple sensors together
    - E.g., stereo camera rig
  - ➢ Sparse or dense sensors
    - E.g., digital camera is dense 2D array of intensity sensor with know angles
  - ➢ Technical issues with multiple sensors
    - Sensor synchronization
      – Ensure simultaneous acquisition of measurements
    - Sensor fusion
      – Combining multiple sensor inputs to obtain accurate measurements

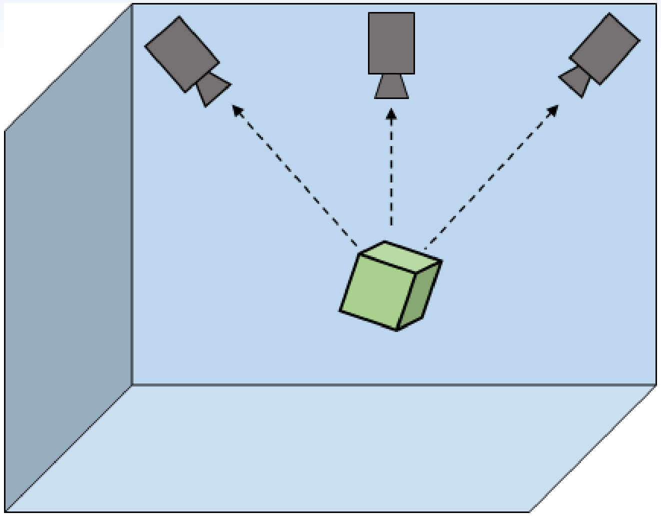


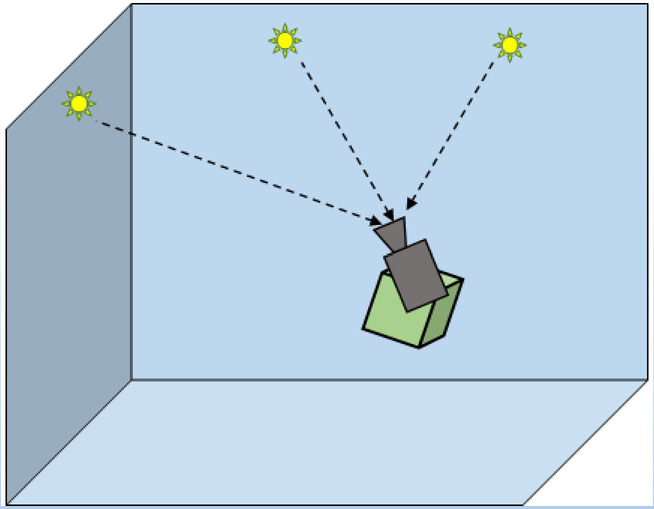
Tracking a target from two cameras.

Source: Doerner, Broll, Grimm, Jung (Eds.): Virtual and Augmented Reality (VR/AR), Springer, 2021

Characteristics of Tracking Technology

- Spatial sensor arrangement
  - ➢ Outside-in tracking
    - Stationary mounted sensors
      - Good position, poor orientation
      - User mostly unaffected by sensor properties, e.g, weight, power
      - Limited workspace
  - ➢ Inside-out tracking
    - Mobile sensor(s)
      - Good orientation, poor position
      - More independent of stationary structures
      - Disadvantage: weight, size, number of sensors

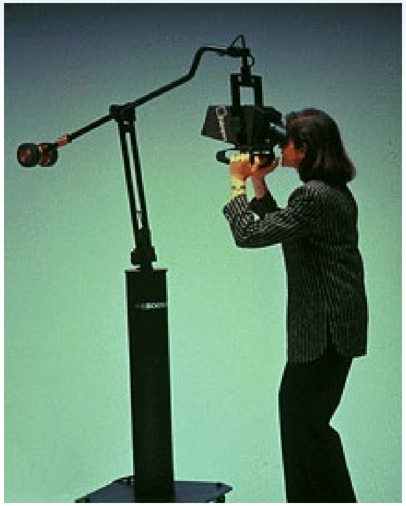




Tracking Systems

- Tracking systems
  - ➢ Choice depends on use case
  - ➢ Need to consider tradeoffs between
    - Performance and cost
    - Size, weight, power consumption
- Stationary Tracking Systems
  - ➢ Mechanical tracking
    - Track end-effector of articulated arm
    - Joints with 2/3 DOF, known lengths
      - – Rotary encoders or potentiometers
    - Fast, high precision
    - Limited freedom of operation

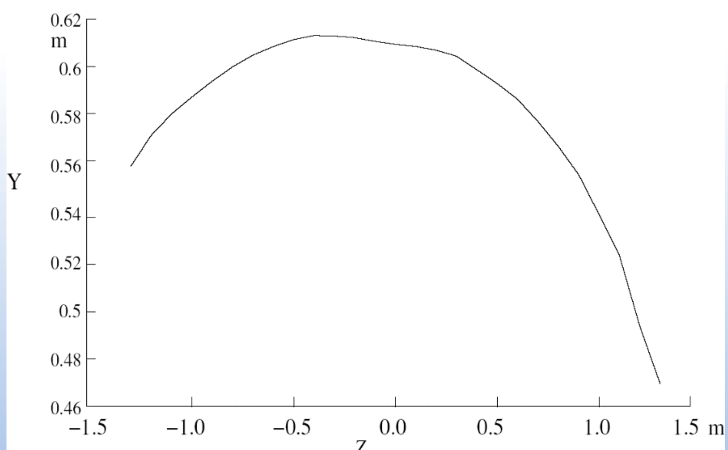
Fakespace BOOM



CyberGrask

Stationary Tracking Systems

- Electromagnetic tracking
  - Stationary source produces three orthogonal magnetic fields
  - Current induced in sensor coils
  - Measurement of strength and phase of signal
    - Does not require open line of sight
    - Signal strength falls off quadratically with distance
    - Working range: half-sphere with 1-3m radius
  - Problems with electromagnetic interference



Razer Hydra

Stationary Tracking Systems

- Ultrasonic Tracking
  - Measures time of flight of sound pulse from source to sensor
  - Trilateration of at least 3 measurements
  - Low update rate (10-50Hz)
    - Due to slow speed of sound
  - Requires open line of sight for clear reception
  - Suffers from noise or change of temperature
  - Wide-area configuration
    - E.g., microphones mounted in ceiling

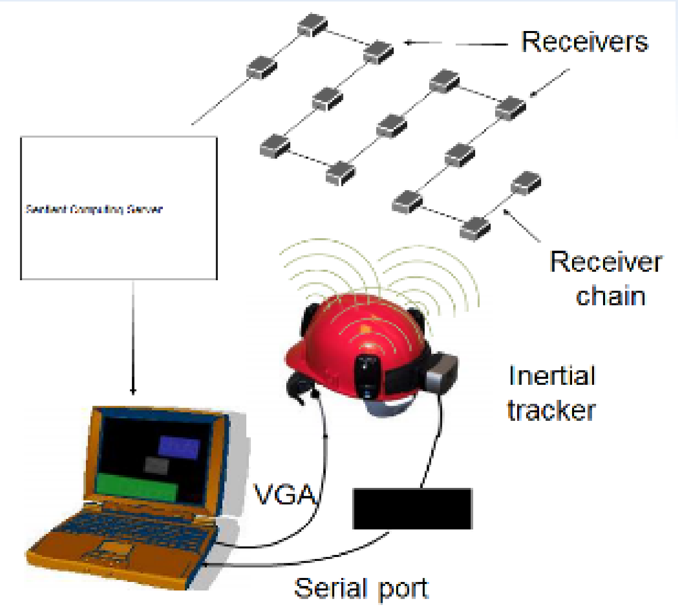
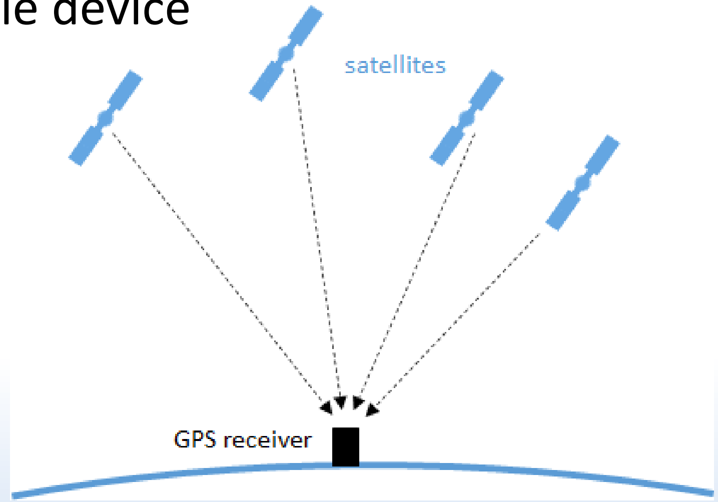


Image: Joseph Newman

Mobile Tracking Systems

- Mobile sensors
  - ➢ Can use outdoors
  - ➢ Sensing and computation for tracking
    - Must be performed locally on the mobile device
      - – Limited processing power
      - – Inexpensive sensors, usually
  - ➢ Global positioning system (GPS)
    - Planet-scale outside-in
      - – Measures radiowave time-of-flight
    - Requires clock synchronization
    - Must receive signals from at least 4 satellites
      - – Known current positions in orbit

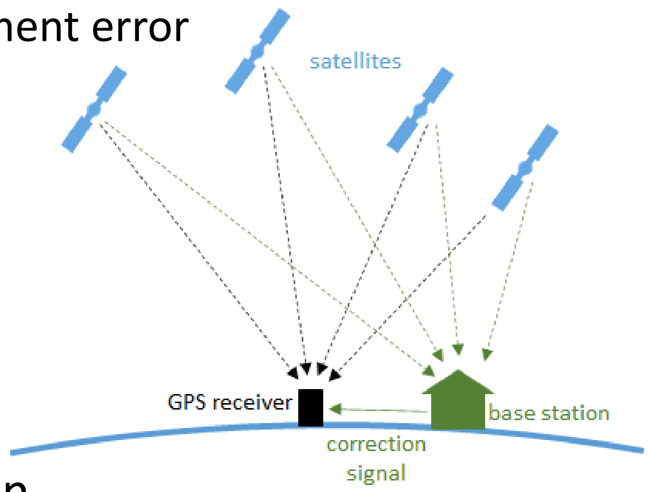


Mobile Tracking Systems

- Often only longitude and latitude used
  - Height significantly affected by measurement error
  - Cannot determine orientation
- Not reliable indoors

➢ Differential GPS

- Higher accuracy than GPS
- Compensate for atmospheric distortion
- Receive correction signal from base station
  - E.g., via permanent Internet connection
- Real-Time Kinematics (RTK) Differential GPS also uses signal phase
  - Improves accuracy to a few cm
  - Size is still too bulky for smartphones

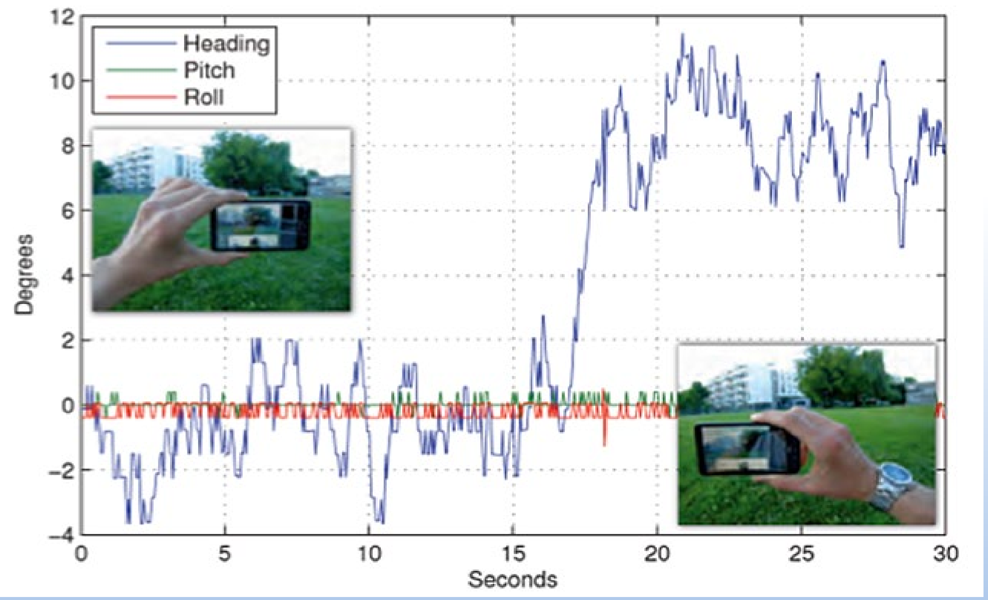


Mobile Tracking Systems

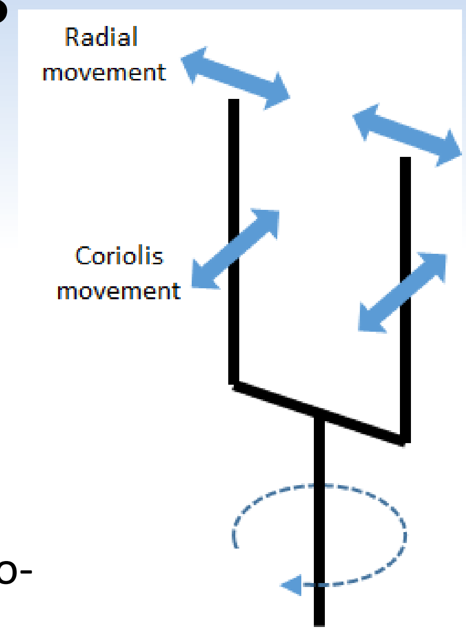
- Wireless networks
  - Measure signal strength from
    - E.g., WiFi, Bluetooth, mobile phone towers
    - Every base station broadcasts a unique ID
      - Potential trilateration/triangulation using location and ID
  - Mostly only good for coarse location
  - Fingerprinting
    - Carefully map the signal reception in a given area
      - E.g., Bluetooth iBeacon in department stores
  - GPS, WiFi and cellular radio capabilities usually available to mobile devices
    - Can combine information from all three to improve coverage, speed and accuracy of position measurement

Mobile Tracking Systems

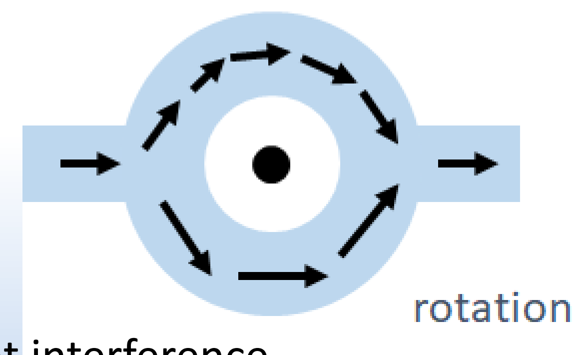
- Magnetometer
  - Electronic compass
    - Measures direction of Earth's magnetic field in 3D
  - Often unreliable, very distorted measurements
    - Distortion from local magnetic fields
      - » Electric and electronic equipment



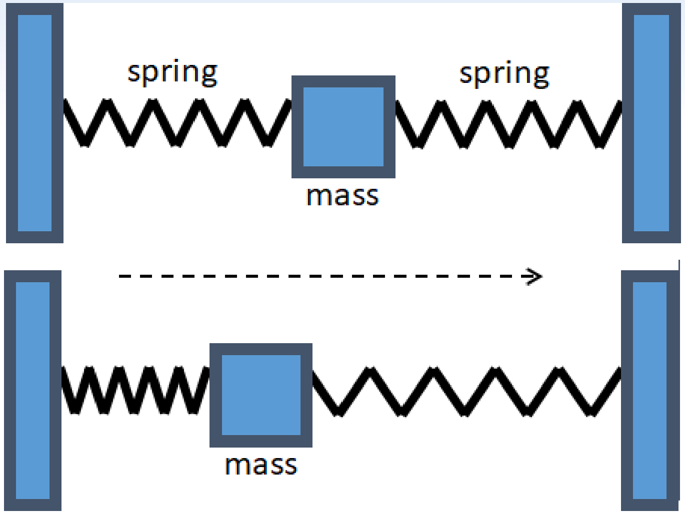
Mobile Tracking Systems



- **Gyroscopes**
  - Measures rotational velocity
    - Determines orientation
  - Electronic gyro
    - Measures Coriolis force of small vibrating object
    - Three orthogonal gyroscopes combined with micro-electromechanical system (MEMS)
      - 3DOF
    - High update rate (1KHz)
    - Only relative measurements
    - Susceptible to accumulated drift
  - Laser gyro (fiber-optic gyro)
    - Measures angular acceleration based on light interference
    - Large, expensive, used in aviation



Mobile Tracking Systems



- Linear accelerometer
  - MEMS device
  - Displacement of small mass
  - Measures
    - Change of electric capacity, or
    - Piezoresistive effect of bending
  - Affected by gravity
  - Position determined relative to starting point
    - Drift problems
  - Can determine 2DOF inclination based on direction of gravity
  - Combine with other sensors for 3DOF orientation

Mobile Tracking Systems

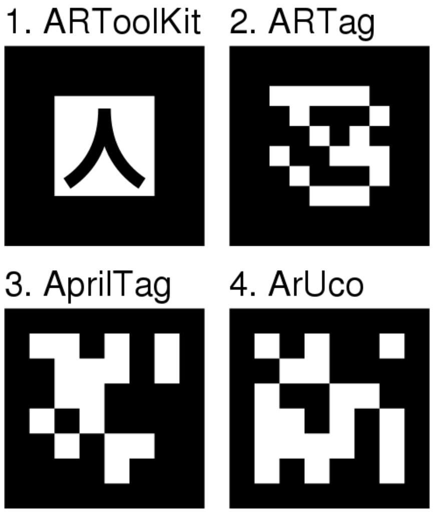
- Odometer
  - Incrementally measure distance traveled over ground
  - Mechanical or opto-electrical wheel encoder
    - E.g., inexpensive odometers in traditional ball mouse

Optical Tracking Systems

- Optical tracking
  - One of the most important physical tracking principles used today
  - Optical sensors
    - Digital cameras are cheap and powerful
      - CCD (charge coupled devices)
        - » Professional photography
      - CMOS (complementary metal oxide semiconductor)
        - » Fast, cheap, low power consumption
    - Inexpensive cameras can provide rich measurements
      - Analysed with sophisticated computer vision techniques
    - Lenses are becoming the most limiting part

Optical Tracking Systems

- Model-based versus model-free tracking
  - Using images from a camera requires comparing with some reference model
  - Model-based
    - A tracking model is available
      - Reference model obtained before tracking
    - Compare the model to observations in the images
  - Model-free
    - At start-up, no tracking model is available
      - More flexible
    - Most build a temporary tracking model while tracking
    - Measurements only relative to starting point



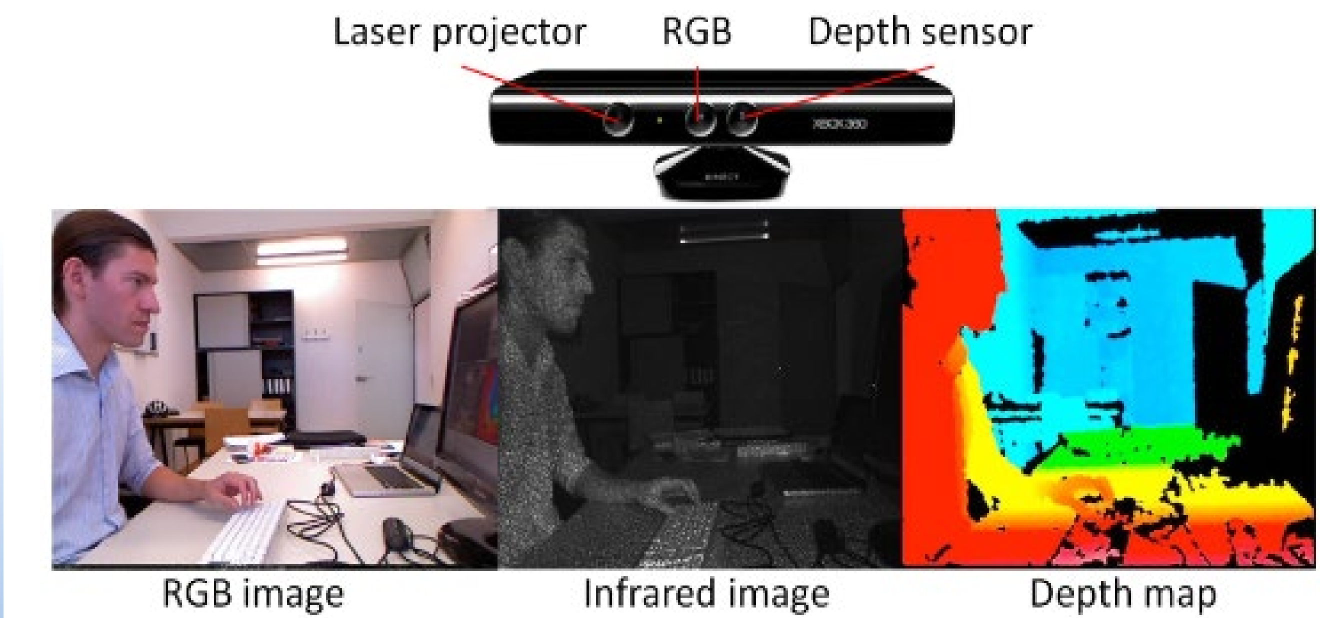
Optical Tracking Systems

- Illumination
  - Passive illumination
    - Natural light sources
      - Not part of the tracking system
    - Can use conventional digital camera
    - Requires sufficient contrast
      - Cannot track when it is too dark (mostly indoors)
  - Active illumination
    - Overcomes dependence on natural light sources
    - Often infrared spectrum
      - Outside human visible spectrum
    - LED beacons
    - Camera with infrared filter delivers high contrast
    - Not suitable with sunlight
      - Infrared frequencies

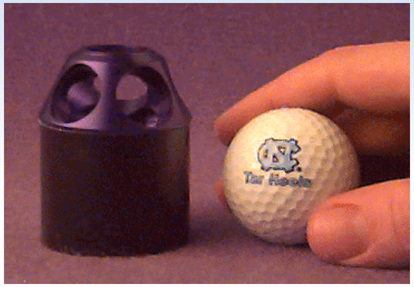
https://www.ign.com/articles/2006/11/29/making-sense-of-the-sensor-bar
Greyson Orlando, Public domain, via Wikimedia Commons

Optical Tracking Systems

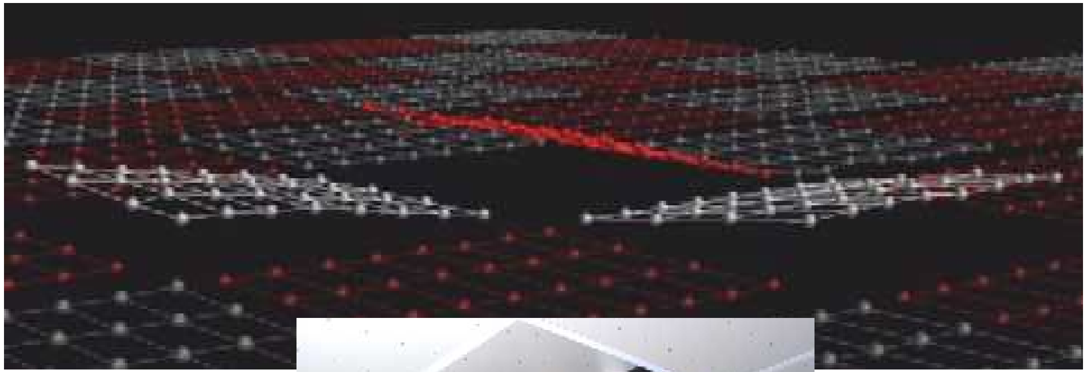
- Structured light
  - Project a known pattern into the scene
  - Projector with regular light or laser
  - Laser ranging
    - » Measure time of flight taken by laser pulse
    - » LIDAR (light radar): long range laser used in surveying



Optical Tracking Systems



- UNC HiBall tracker
  - ➢ User mounted optical sensor
  - ➢ Infrared LEDs installed in special ceiling panels



https://www.cs.unc.edu/~tracker/media/html/hiball.html
https://www.cs.unc.edu/~keller/Tracker/shotgun2.html

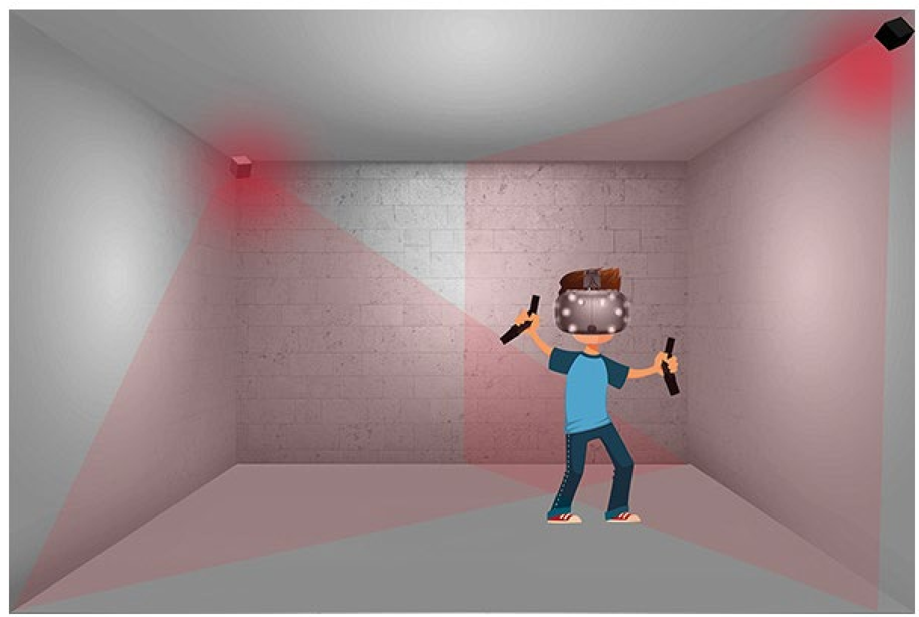
Optical Tracking Systems

- Leap Motion Controller
  - Optical hand tracking
  - 2 cameras, 3 infrared LEDs
  - Short-distance reflection of hands

https://www.ultraleap.com/product/leap-motion-controller/

Optical Tracking Systems

- Valve Index/HTC Vive
  - “Lighthouses” – two scanning infrared lasers
  - Photodiodes on headset and controllers pick up lasers



Room image and character by stryjekk, subarashii21 © [123RF.com](123RF.com) —Derivative work—S. Auksakalnis

Optical Tracking Systems

- Markers vs natural features
  - Optical tracking problems
    - Insufficient identifiable features
      - E.g., white wall
    - High specularity
      - Unstable when moved relative to camera
    - Repetitive textures
      - E.g., table cloth
  - Markers
    - Known patterns
    - Designed to make detecting their appearance in images to be easy and reliable
    - Specific shape, optimal contrast

Optical Tracking Systems

- Markers vs natural features
  - Fiducial markers
    - Artificial tracking targets
    - Square shapes yield 4 points (track pose)
    - Circular shapes yield only 1 point
    - Digital marker model exists first, marker manufactured second (e.g., printing)
  - Natural feature tracking
    - Existing visual features in the environment
    - Physical features exist first, tracking model reconstructed second

Image: Daniel Wagner
Image: Andrei State, UNC Chapel Hill

Optical Tracking Systems

- Flat marker designs

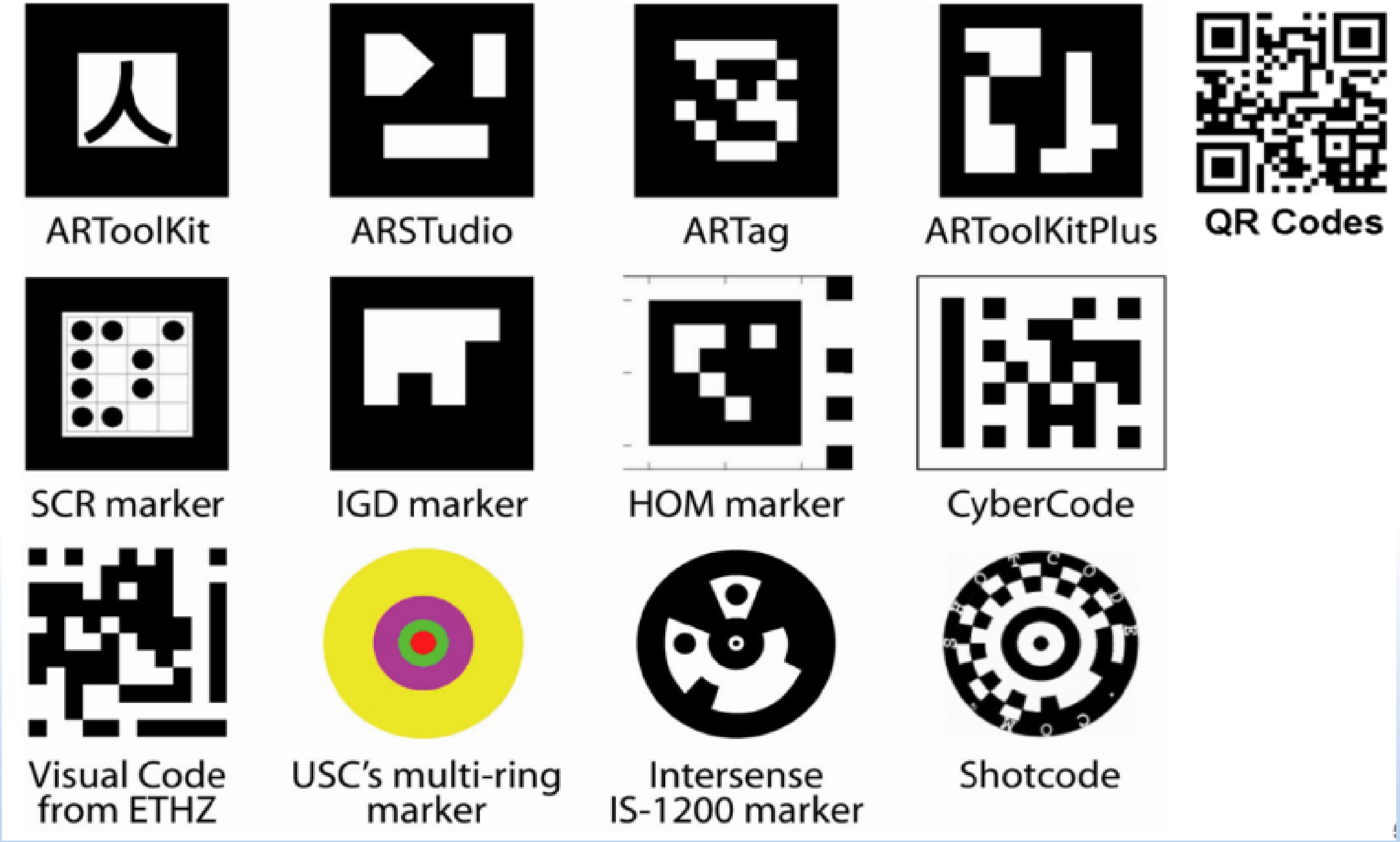
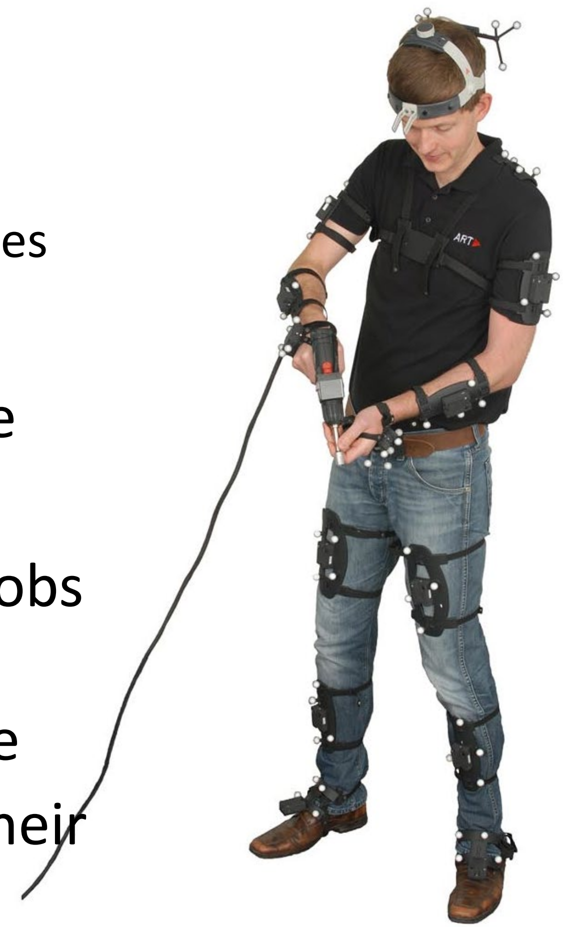


Image: Daniel Wagner

Optical Tracking Systems

- Flat markers
  - ➢ Problem: flat surface
  - ➢ Spheres
    - Always project to a disc shape in images
- Retro-reflective ball markers
  - ➢ Light reflected towards light-source
  - ➢ Illuminate with infrared LED flash
  - ➢ Infrared camera observes bright blobs
  - ➢ 4 or more spheres in known configuration to recover 6DOF pose
  - ➢ Multiple targets distinguished by their geometric configuration



Source: Doerner, Broll, Grimm, Jung (Eds.): Virtual and Augmented Reality (VR/AR), Springer, 2021

Recording of body movements (© ART 2013, all rights reserved).

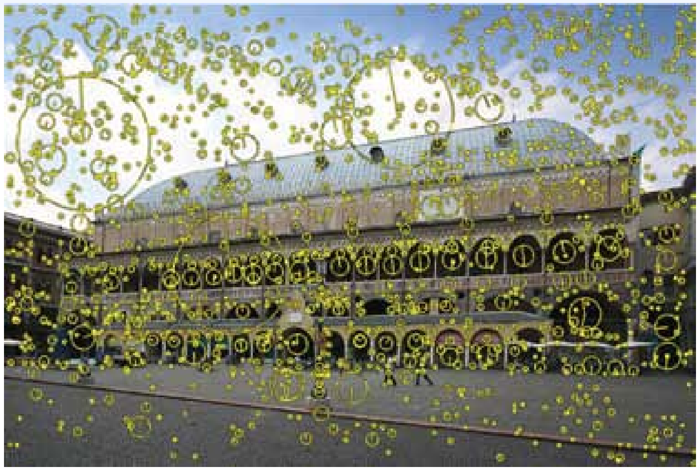
Optical Tracking Systems

- Reflective markers
  - ➢ Full body tracking

Optical tracking of a person with reflective markers (the markers appear to be illuminated by the flashlight used) and several infrared cameras (infrared LEDs appear red).

Optical Tracking Systems

- Natural features
  - Requires better image quality and more computational resources
  - Interest points/keypoints
    - Detect salient interest points in image
      - » Must be easily found
      - » Location in image should remain stable when viewpoint changes
      - » Requires textured surfaces
    - Edge features
      - » Less discriminative to texture
      - » Multiple edges must be jointly interpreted for reliable target detection



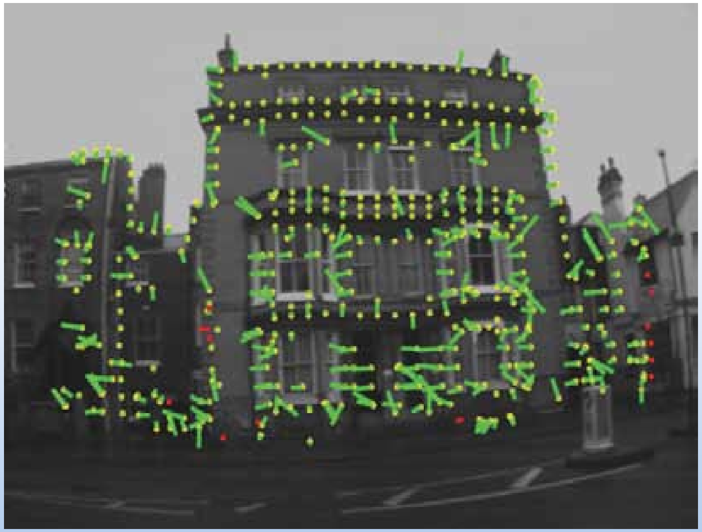


Image: Martin Hirzer
Image: Gerhard Reitmayr

Optical Tracking Systems

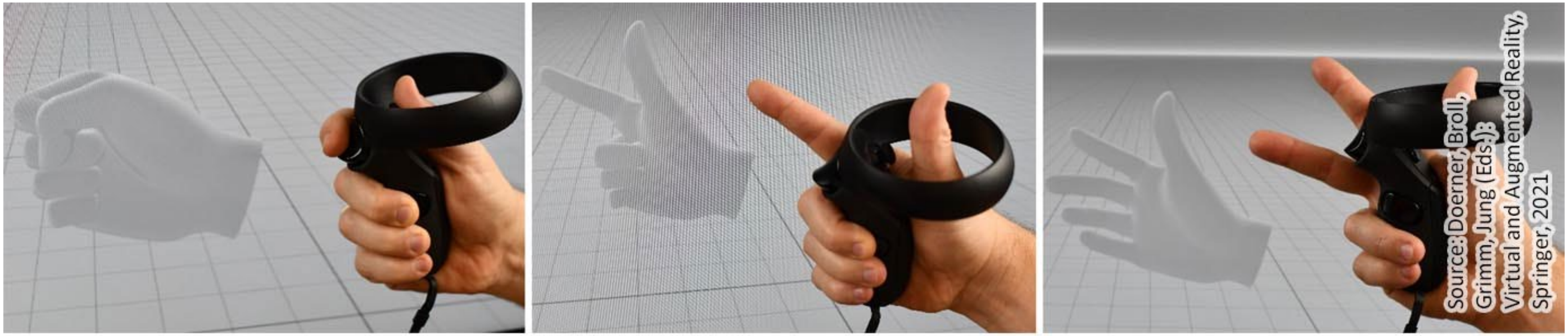
- Match interest points to tracking model database
  - Database filled with results of 3D reconstruction
  - Matching entire (sub-)images is too costly
  - Typically interest points are compiled into “descriptors”

➢ Marker target identification

- More targets or features
  - Easily confused
- Must be as unique as possible
- Spherical targets
  - 5 spheres in different geometric configurations
    - » Can distinguish 10-20 targets
- Pulsed LEDs

Tracking Systems

- Touch sensitive surfaces



3D model of a hand controlled by a VR controller with touch sensors.

References

- Among others, material sourced from
  - S. Aukstakalnis, Practical Augmented Reality: A Guide to the Technologies, Applications, and Human Factors for AR and VR, Addison-Wesley
  - D. Schmalstieg and T. Hollerer, Augmented Reality: Principles and Practice, Addison-Wesley
    - www.augmentedrealitybook.org
  - R. Doerner, W. Broll, P. Grimm, B. Jung, Virtual and Augmented Reality: Foundations and Methods of Extended Realities, Springer
  - http://en.wikipedia.org/wiki/