Tracking and Sensing for Mixed and Virtual Reality

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Structure

- Part 1: Introduction
  - Motivation
  - Requirements of the Ideal Tracking System
  - Types of Tracking Systems
- Part 2: Different Tracking Technologies
  - Legacy Tracking Technologies
  - Current Tracking Systems
  - Hybrid Tracking Systems
- Part 3: Case Studies
  - Oculus Rift
  - Microsoft HoloLens
  - Mobiles Phones (ARKit / ARCore)

Motivation

- **Part 1: Introduction and Motivation**
  - **Motivation**
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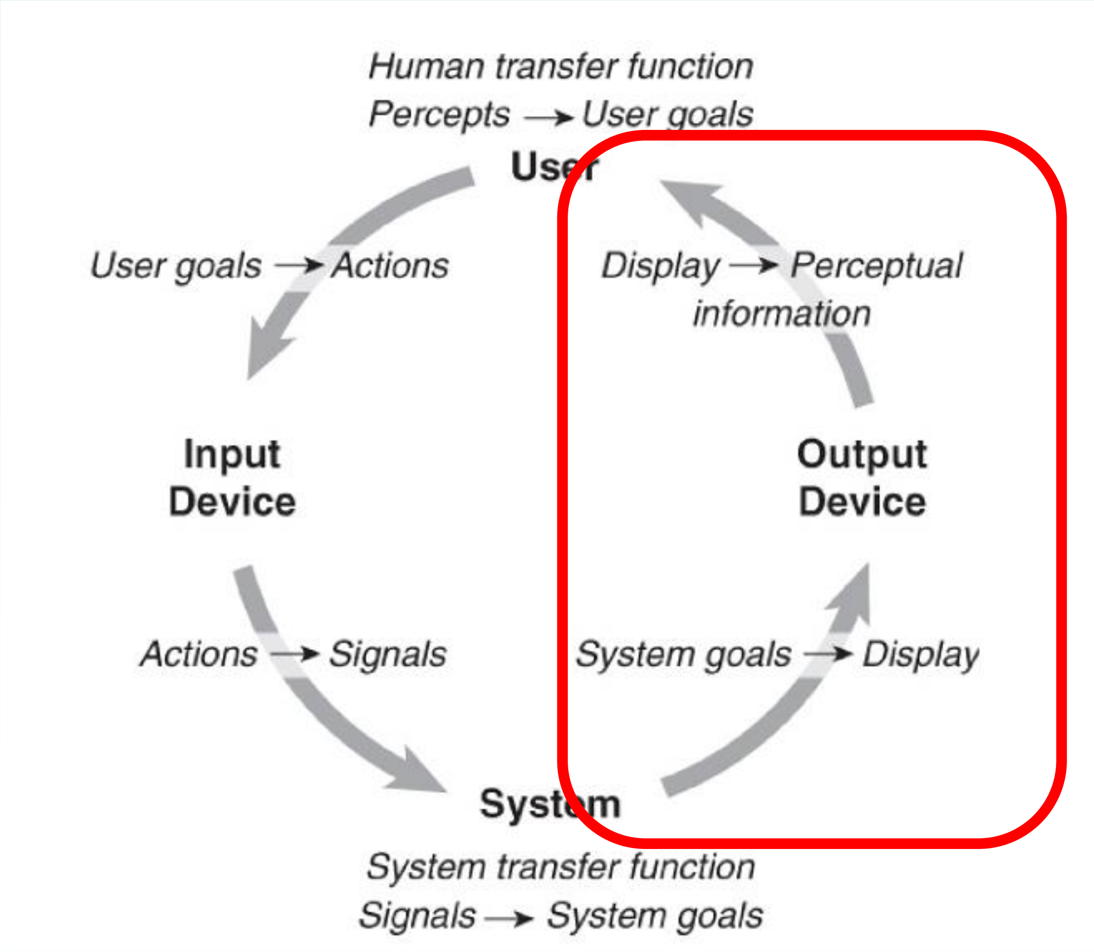
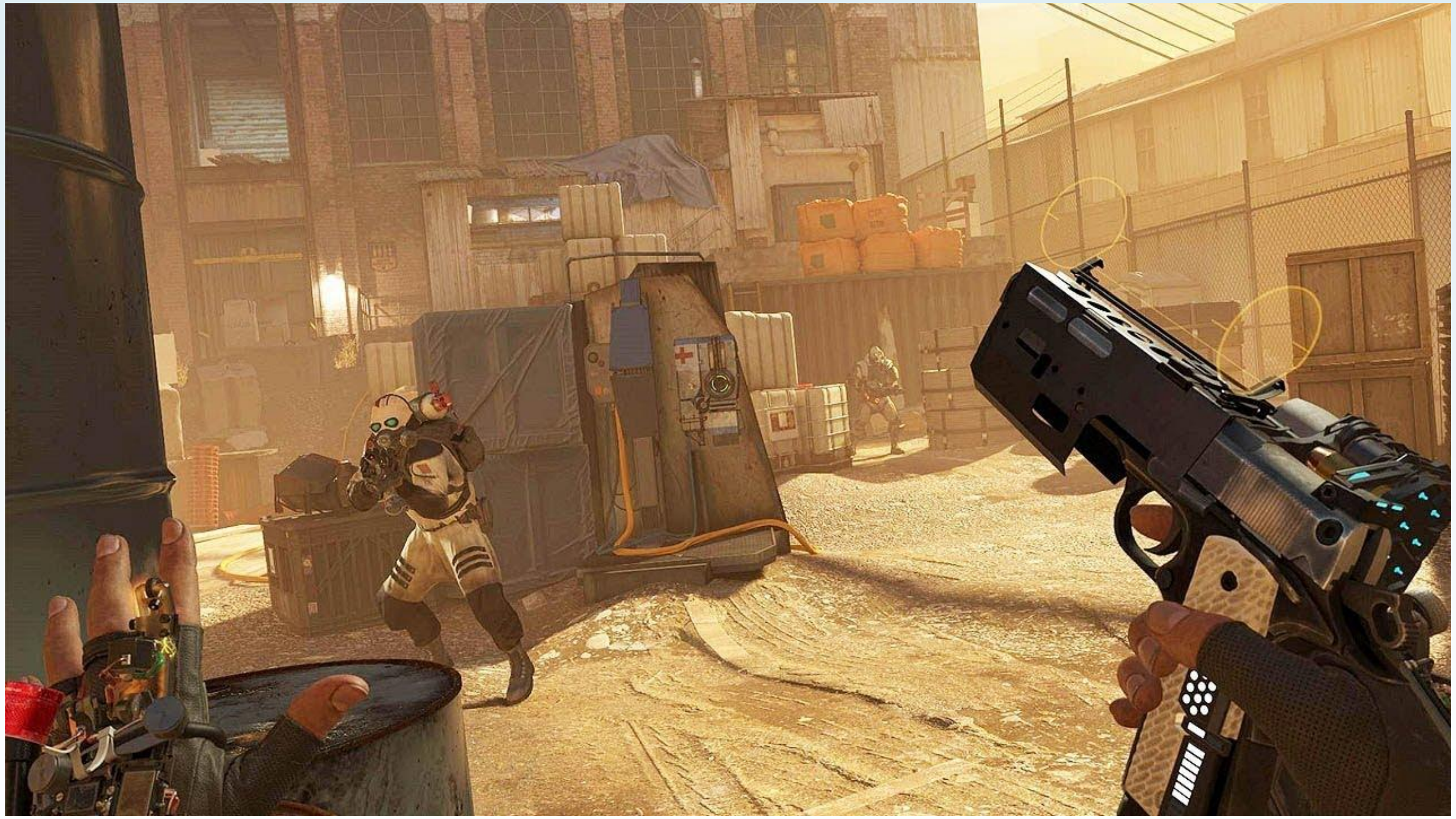
Motivation



Bowman et al, 2004

Motivation



From “Even More Interaction in Half-Life Alyx”

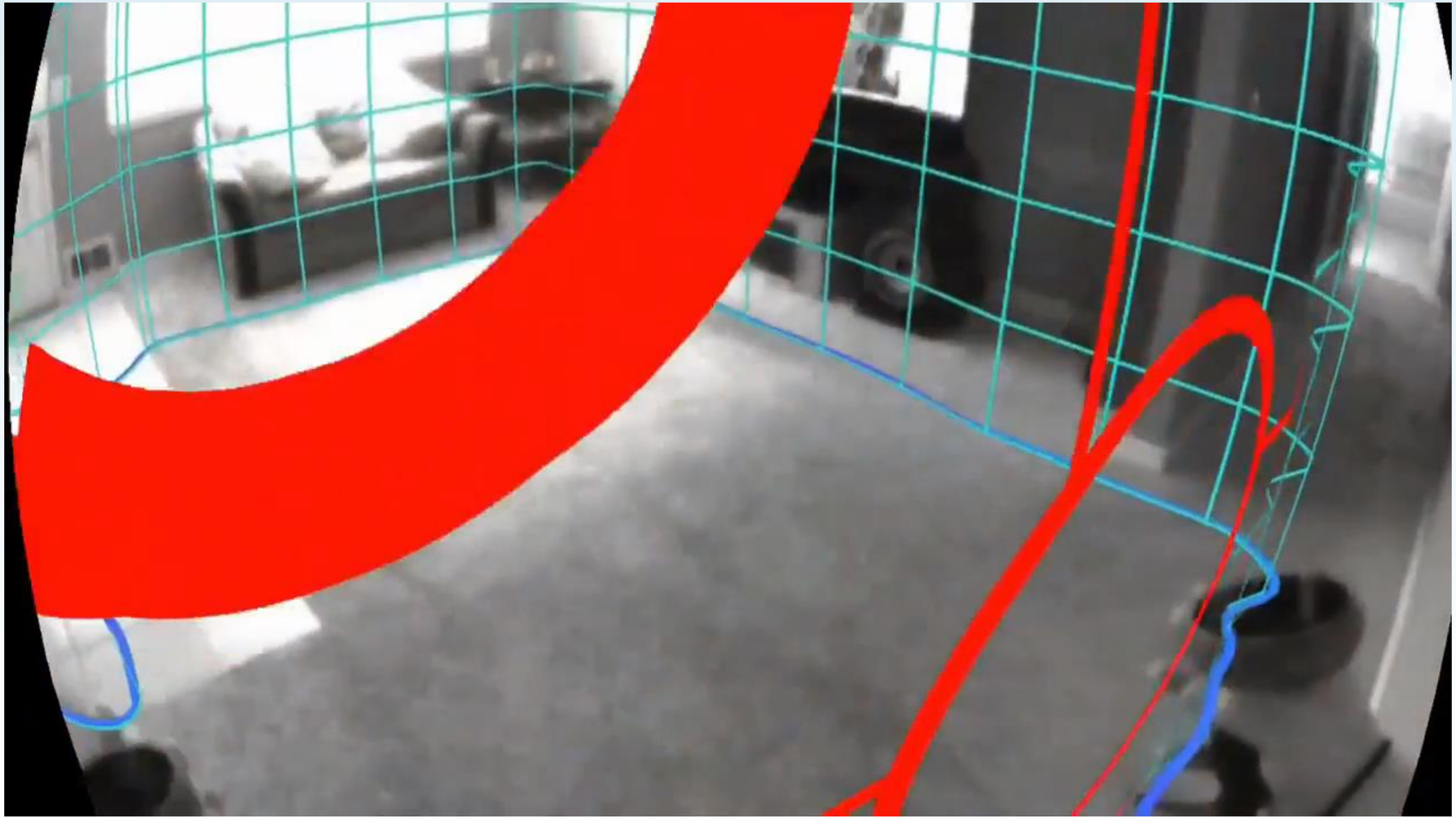
Fragments Gameplay

From “Gameplay Fragments for Hololens - Becoming a Memory Investigator”

Useful for Safety Too…

Photo by [Euegene Capon]

Oculus Quest Guardian System



From Oculus Quest: Guardian Setup and Demo

Requirements of the Ideal Tracking System

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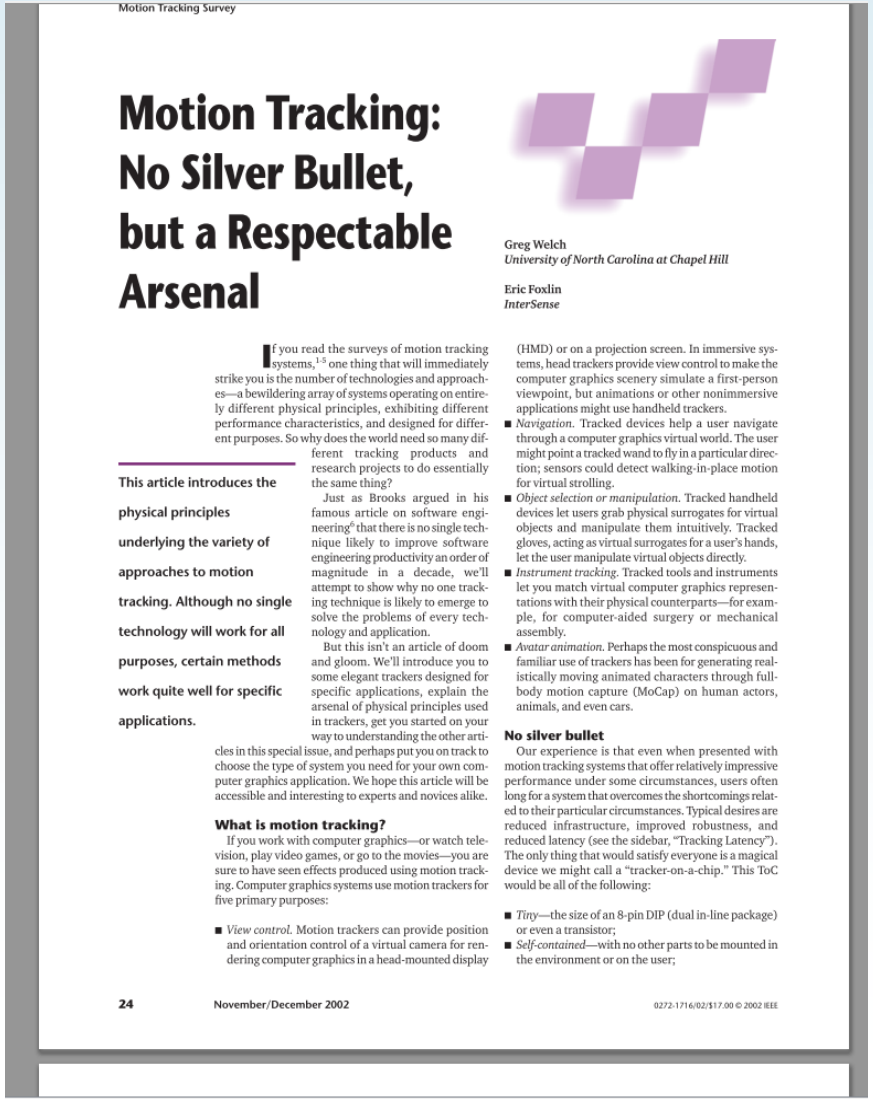
  - *Oculus Rift*
  - *Microsoft HoloLens*
  - *HTC VIVE*

Requirements of the Ideal Tracking System

Magical, ideal tracker would have these characteristics:

- Accurate (1mm position, 0.1 degree orientation)
- Fast (1000Hz, <1ms latency)
- Tiny (transistor size)
- Complete (6 DoF)
- Immune to occlusions (no line-of-sight requirement)
- Robust (no interference)
- Self-Contained
- No range limitation
- Cheap



Motion Tracking: No Silver Bullet, but a Respectable Arsenal

Greg Welch
University of North Carolina at Chapel Hill

Eric Foxlin
InterSense

This article introduces the physical principles underlying the variety of approaches to motion tracking. Although no single technology will work for all purposes, certain methods work quite well for specific applications.

If you read the surveys of motion tracking systems,[1-5] one thing that will immediately strike you is the number of technologies and approaches—a bewildering array of systems operating on entirely different physical principles, exhibiting different performance characteristics, and designed for different purposes. So why does the world need so many different tracking products and research projects to do essentially the same thing?

Just as Brooks argued in his famous article on software engineering[6] that there is no single technique likely to improve software engineering productivity an order of magnitude in a decade, we'll attempt to show why no one tracking technique is likely to emerge to solve the problems of every technology and application.

But this isn't an article of doom and gloom. We'll introduce you to some elegant trackers designed for specific applications, explain the arsenal of physical principles used in trackers, get you started on your way to understanding the other articles in this special issue, and perhaps put you on track to choose the type of system you need for your own computer graphics application. We hope this article will be accessible and interesting to experts and novices alike.

What is motion tracking?

If you work with computer graphics—or watch television, play video games, or go to the movies—you are sure to have seen effects produced using motion tracking. Computer graphics systems use motion trackers for five primary purposes:

- *View control.* Motion trackers can provide position and orientation control of a virtual camera for rendering computer graphics in a head-mounted display (HMD) or on a projection screen. In immersive systems, head trackers provide view control to make the computer graphics scenery simulate a first-person viewpoint, but animations or other nonimmersive applications might use handheld trackers.
- *Navigation.* Tracked devices help a user navigate through a computer graphics virtual world. The user might point a tracked wand to fly in a particular direction; sensors could detect walking-in-place motion for virtual strolling.
- *Object selection or manipulation.* Tracked handheld devices let users grab physical surrogates for virtual objects and manipulate them intuitively. Tracked gloves, acting as virtual surrogates for a user's hands, let the user manipulate virtual objects directly.
- *Instrument tracking.* Tracked tools and instruments let you match virtual computer graphics representations with their physical counterparts—for example, for computer-aided surgery or mechanical assembly.
- *Avatar animation.* Perhaps the most conspicuous and familiar use of trackers has been for generating realistically moving animated characters through full-body motion capture (MoCap) on human actors, animals, and even cars.

No silver bullet

Our experience is that even when presented with motion tracking systems that offer relatively impressive performance under some circumstances, users often long for a system that overcomes the shortcomings related to their particular circumstances. Typical desires are reduced infrastructure, improved robustness, and reduced latency (see the sidebar, "Tracking Latency"). The only thing that would satisfy everyone is a magical device we might call a "tracker-on-a-chip." This ToC would be all of the following:

- *Tiny*—the size of an 8-pin DIP (dual in-line package) or even a transistor;
- *Self-contained*—with no other parts to be mounted in the environment or on the user;

Dynamics Are Very Challenging

- Head tracking is very severe
- Highly aggressive movement:
  - Peak angular velocity 520 deg / s
  - Peak angular acceleration 53,360 deg / s^2

- Other body parts (especially hands) are also very aggressive

“Linear and Angular Head Accelerations in Daily Life”, W. R. Bussone, 2005

Challenges with Latency

- Strong link between vestibular system and vision system
  - Peripheral vision particularly sensitive to movement

- Fast coupling between movement and update of graphics required
  - Failure to do so leads to nausea and simulator sickness

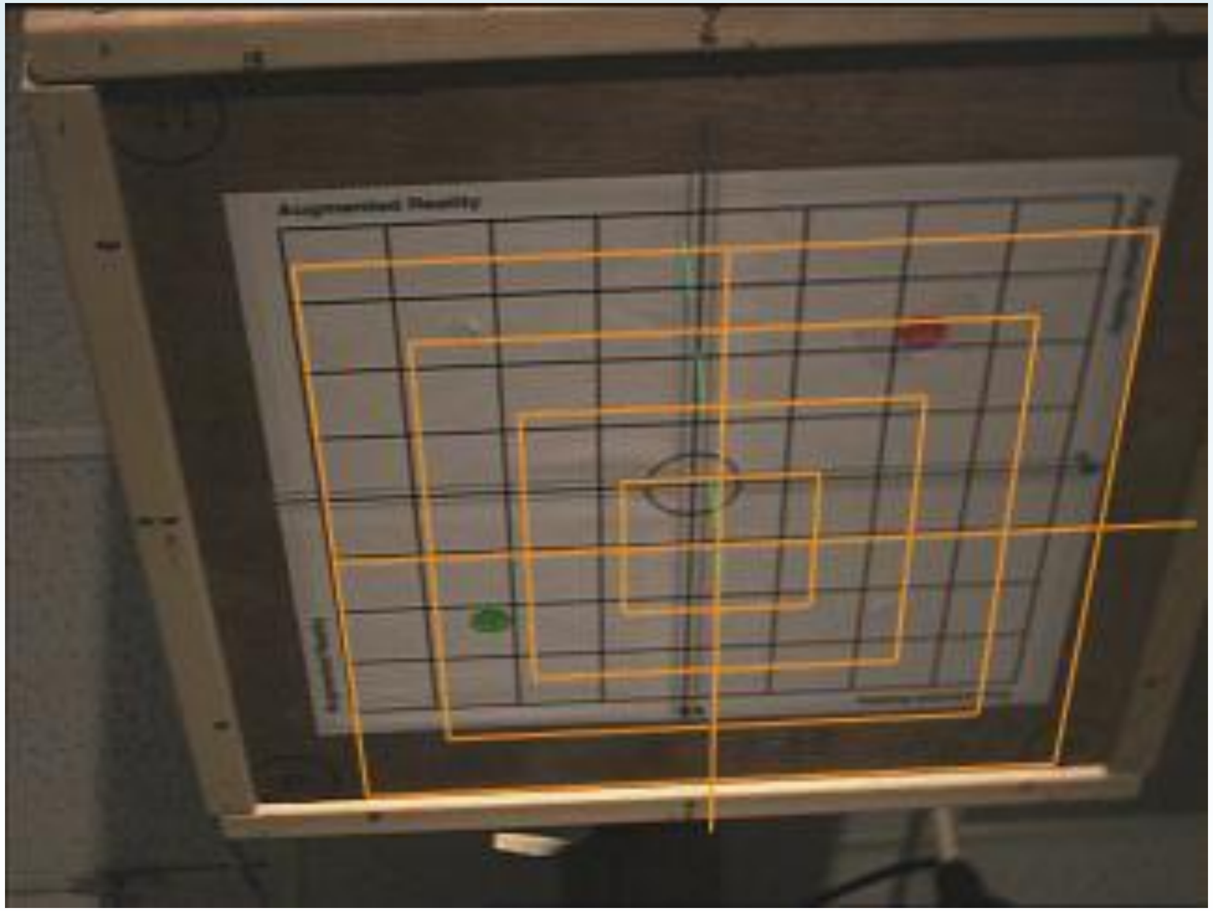
- People have traditionally argued that 50ms is sufficient
  - However, studies have shown that effects start to kick in *at 17ms*

Consistency with the Environment

- VR and AR have different requirements with respect to their tracking accuracy

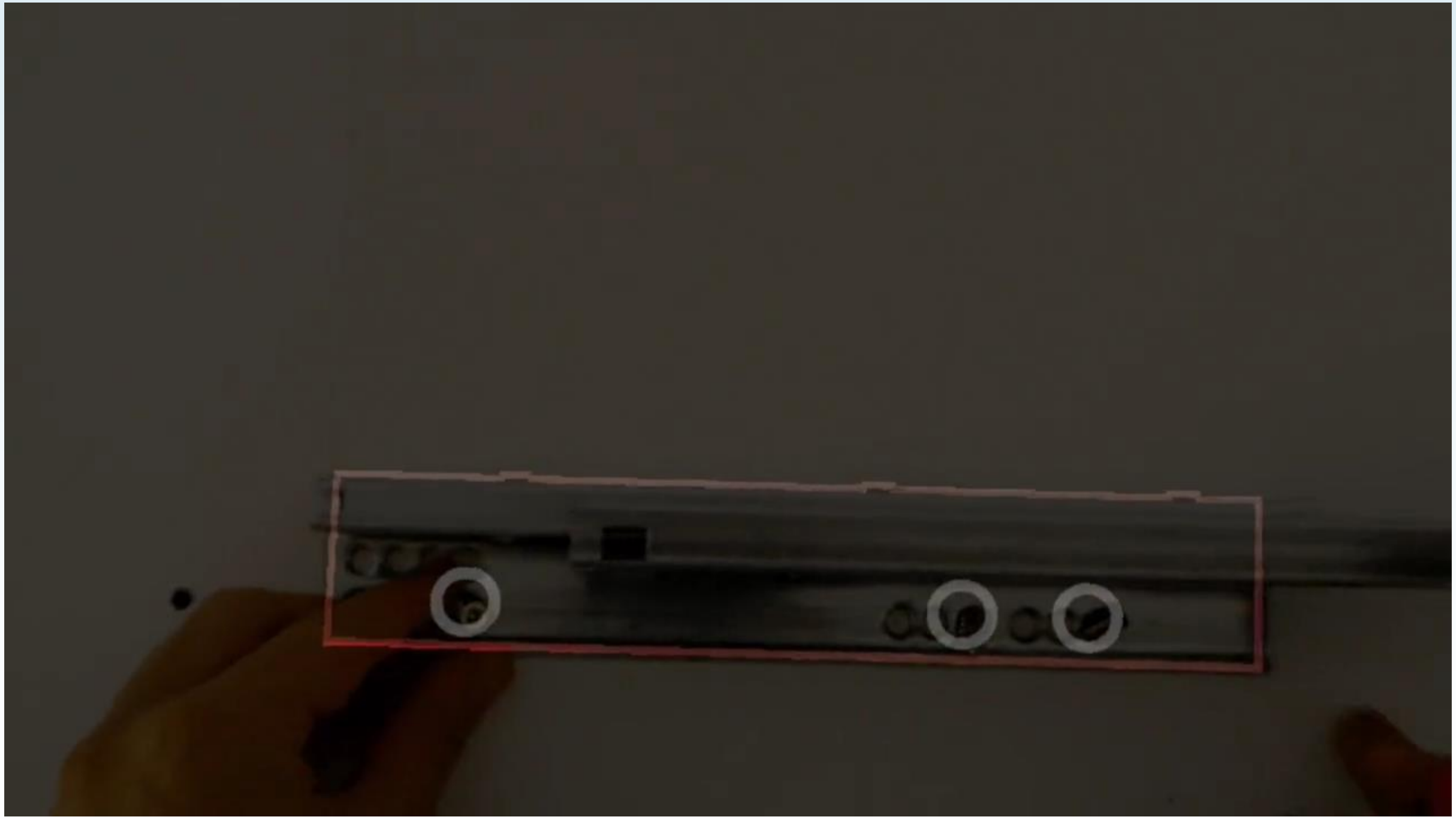
- AR systems need to be externally consistent with respect to the world

Tracking Errors of < 0.1 Degree Very Obvious



From “Registration Errors in Augmented Reality Systems”

External Consistency with AR



Augmented reality misalignment (UCL)

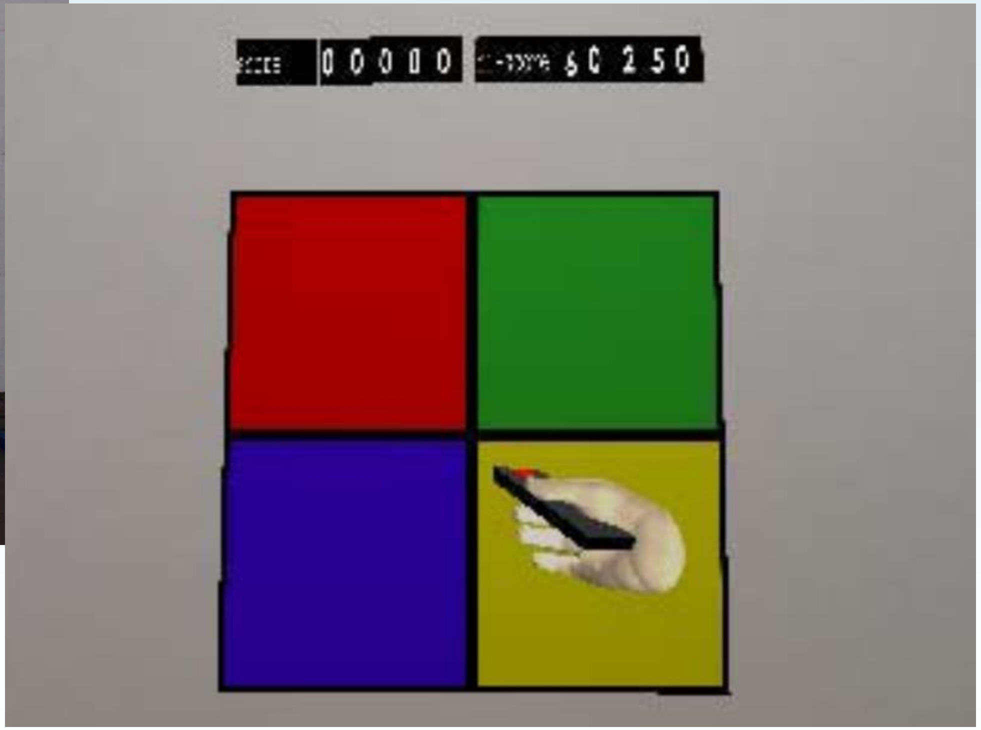
Consistency with the Environment

- VR and AR have different requirements with respect to their tracking accuracy

- AR systems need to be externally consistent with respect to the world

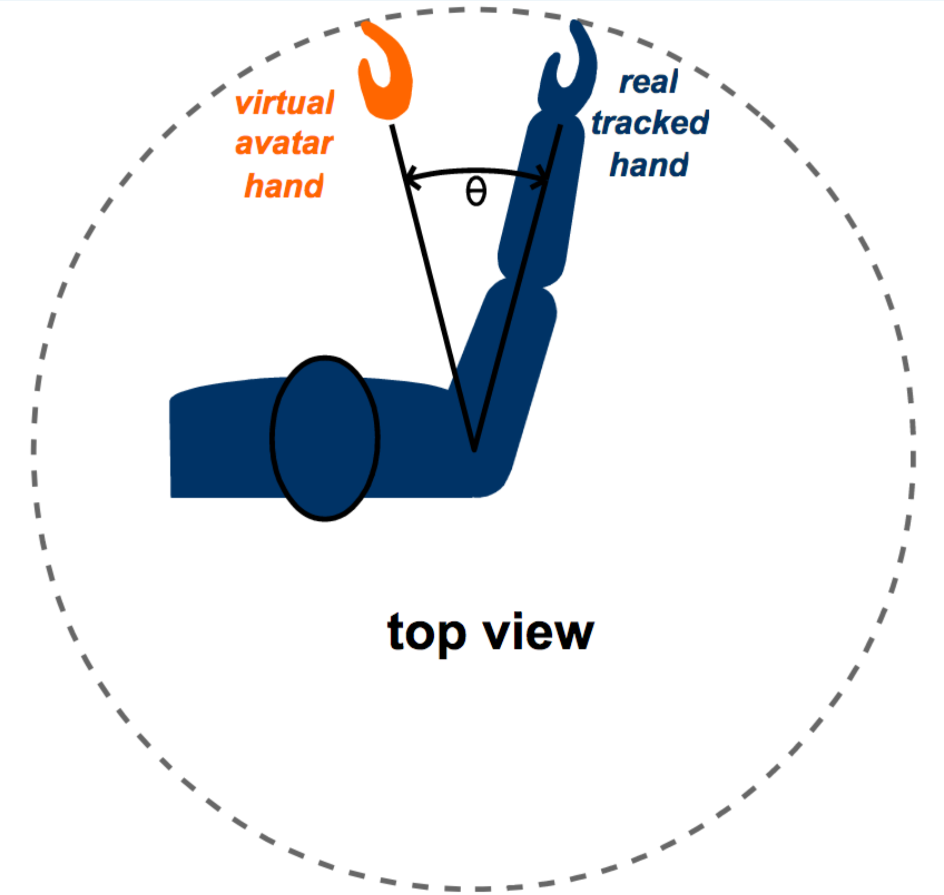
- VR systems need to be internally consistent with respect to the virtual objects

Internal Consistency in VR



“The Hand is Slower than the Eye: A quantitative exploration of visual dominance over proprioception”, E. Burns, 2005

Internal Consistency in VR



“The Hand is Slower than the Eye: A quantitative exploration of visual dominance over proprioception”, E. Burns, 2005

Characterising Tracking Systems

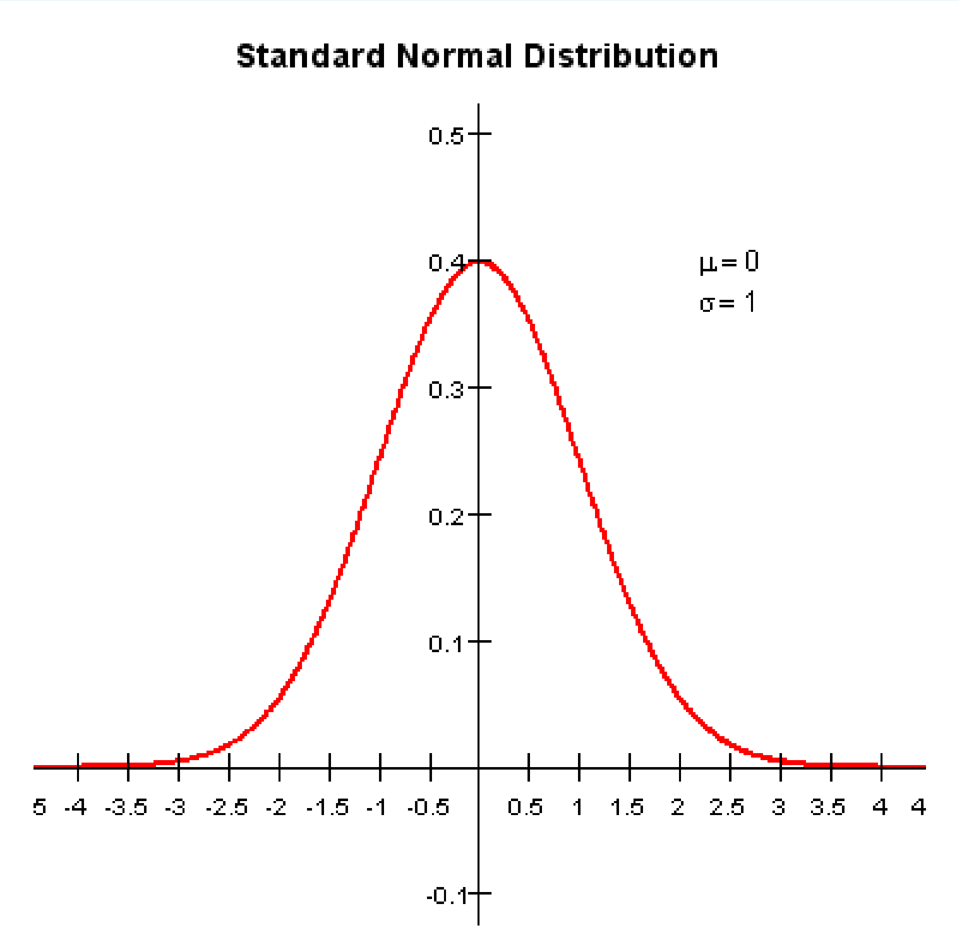
- Accuracy
  - The error in the positions reported by the system
- Precision
  - The size of the range of the correct positions reported by the system
- Sample Rate
  - The frequency the system delivers new data
- Latency
  - the delay between the new movement made and the new position reported
- Number of tracked objects
  - How does the number of individual points and objects that can be tracked scale

Characterising Tracking Systems

- Size
  - The physical footprint of the systems hardware, both on the tracked item and in the environment
- Range
  - The area/range/volume in which the tracker can accurately report the positions. E.g., the distance, the height. This is determined by the wire length, signal strength, etc.
- Cost
  - Or, equivalent cost per tracked object, factoring in every component
- Reliability/Robustness
  - How does accuracy change with time and environmental conditions

Error in Tracking Systems (Accuracy)

- Bias
  - A persistent error in the reported position
- Noise
  - True stochastic error in the reported position
- Spatial Jitter
  - Range of values that could be reported around the true position
- Temporal Jitter
  - Variation in the timing of the reports (typically for a system that should be synchronous/consistent)



Types of Tracking Systems

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  - *Microsoft HoloLens*
  - *Mobiles Phones (ARKit / ARCore)*

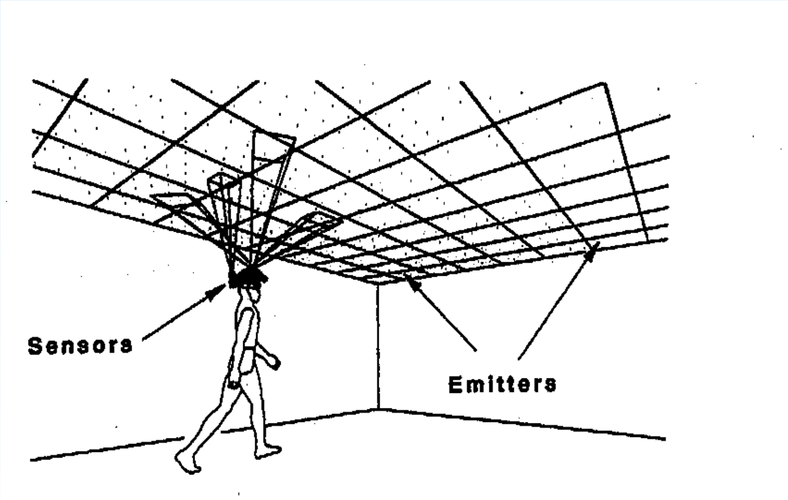
Trackers Come in Various Shapes and Sizes

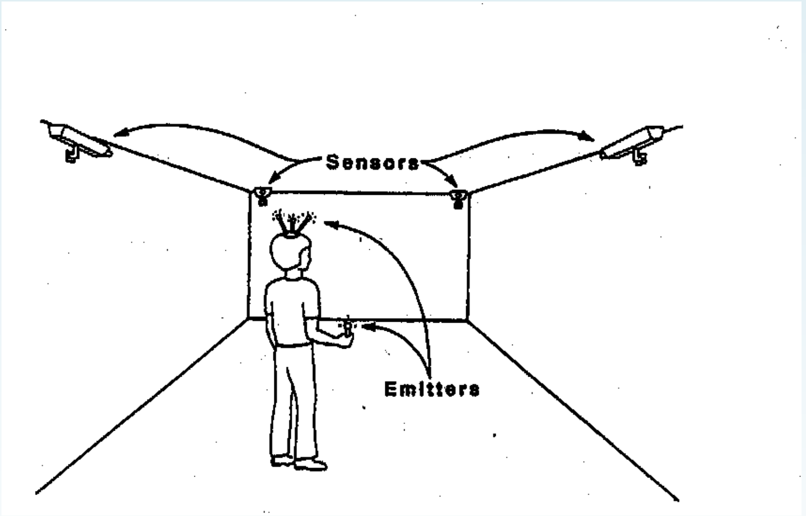
- Is it inside-out or outside-in?
- What parts of the body are tracked?
- Does it monitor the environment or not?

Inside-Out or Outside-In?

- **Is it inside-out or outside-in?**
- *What parts of the body are tracked?*
- *Does it monitor the environment or not?*

Inside-Out vs. Outside-In





Inside-Out
Tracking sensors worn by the user and "looks" at the environment

Outside-In
Tracking sensors part of the environment and "look" at the user

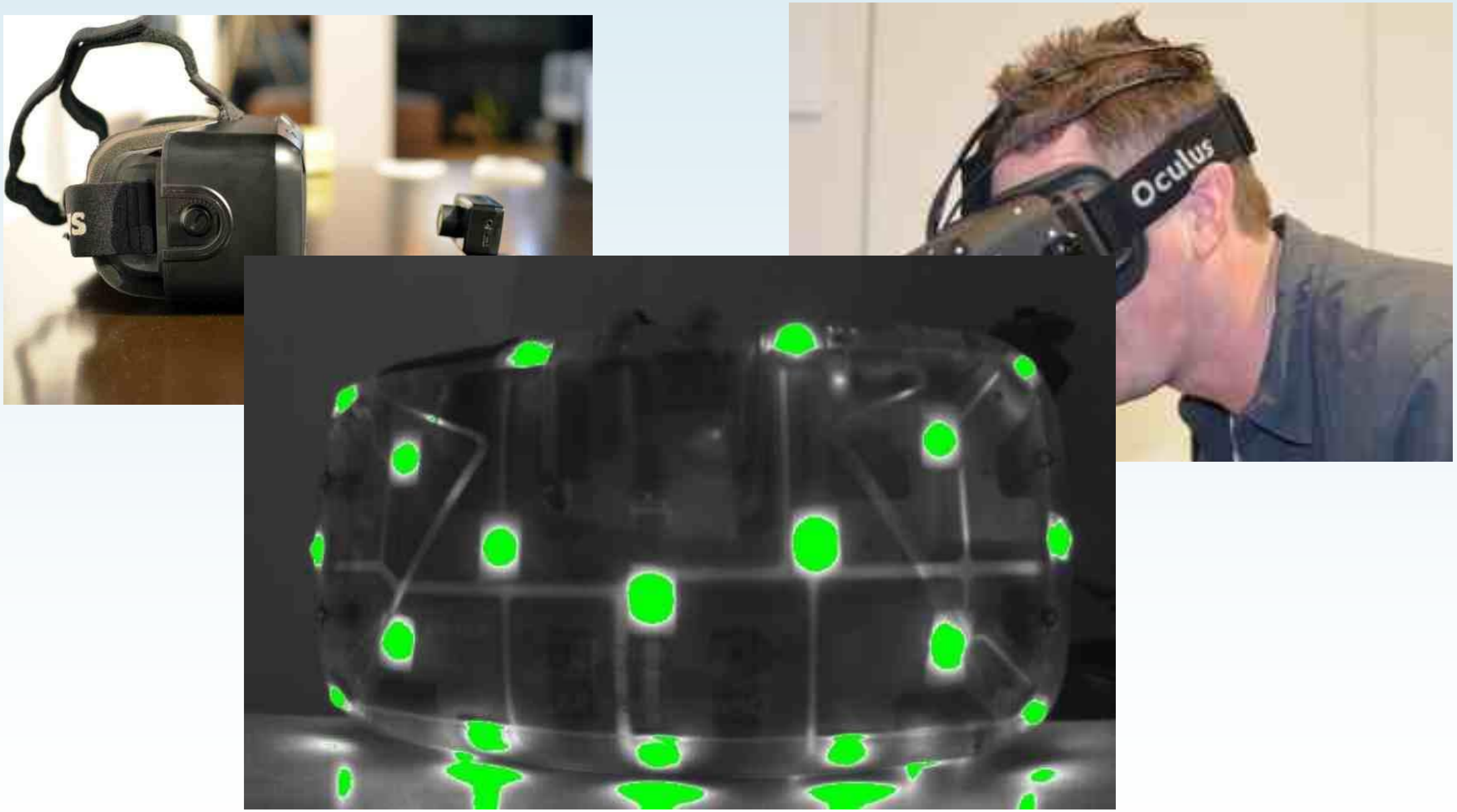
Inside-Out Tracking System

Early Lighthouse Prototype. From "Inside Out Tracking"

Motion Capture Outside-In Tracking System

Vicon Optical Tracker

Oculus Rift Outside-In System



From http://www.roadtovr.com/incredible-performance-oculus-rift-dk2-positional-tracking-ir-camera-video/

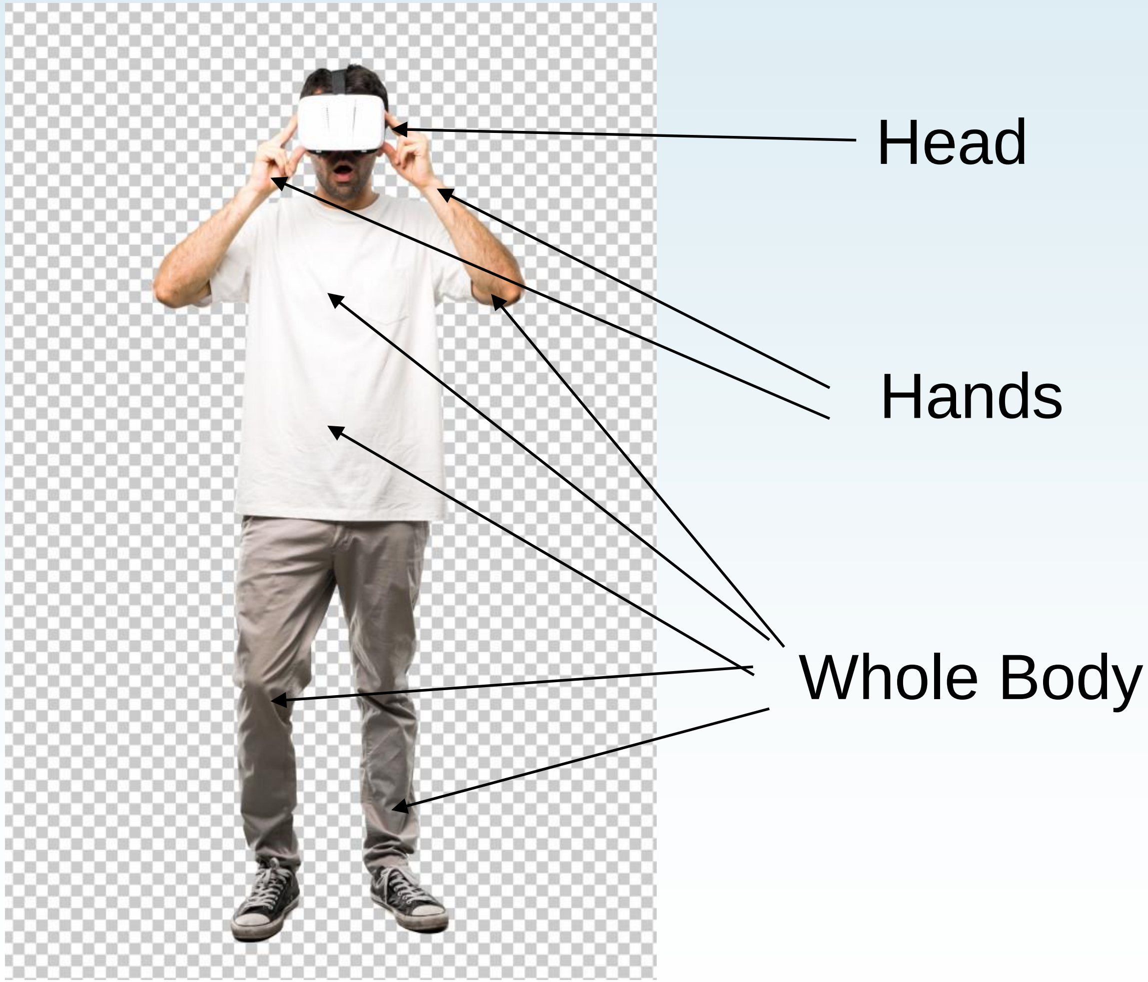
Inside Out vs Outside In Tracking Systems

- Inside-Out:
  - Great flexibility over volume of operation
  - Moore’s Law means that very powerful miniature systems now exist
  - Orientation tracked accurately
- Outside-In:
  - Heavy and power-hungry resources are not fixed to the person
  - A lot of time can be spent doing very precise calibration of the system to give optimal performance
  - Position tracked very accurately

What parts of the body are tracked?

- *Is it inside-out or outside-in?*
- **What parts of the body are tracked?**
- *Does it monitor the environment or not?*

How Much of the Body Do We Track?



Body Tracking

- Advantages:
  - The more parts of the body we can track, the more accurate and expressive our avatars can become
  - This is particularly important for things like finger tracking

- Disadvantages:
  - More substantial sensing is required (cost, putting them on correctly)
  - Accuracy can be low (requires suitable line-of-sight, body pose, etc.)
  - Diminishing returns and computation slows down

Does it monitor the environment or not?

- *Is it inside-out or outside-in?*
- *What parts of the body are tracked?*
- **Does it monitor the environment or not?**

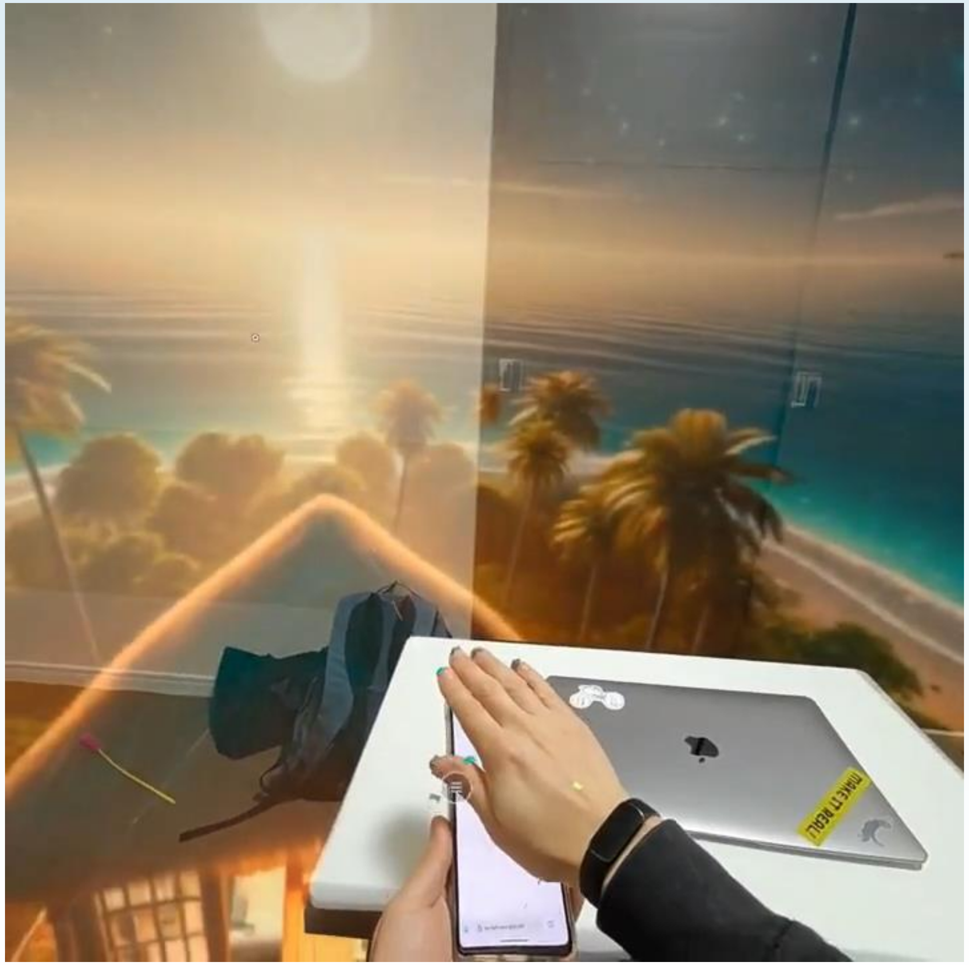
Environment Sensing

- Environment sensing refers to monitoring the real-world physical environment about the user

- Types of information recorded include:
  - Geometry of surrounding environment
  - Light level
  - Sound volume

1. HoloLens 3D Room Mapping

Use of Ambient Light Levels



From “MetaQuest3: Ambient Light Sensor and Mixed Reality”

Environment Sensing

- Advantages:
  - The system understands the context the user is operating in and can adapt accordingly
  - Much richer AR and VR interactions can be developed
- Disadvantages:
  - Requires more sensing
  - Requires processing of the sensor data

Different Tracking Technologies

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Main Types of Tracking Technology

- Mechanical
- Magnetic
- Acoustic

Historically important, niche use today

- Inertial
- Optical
- Hybrid

Very widely used

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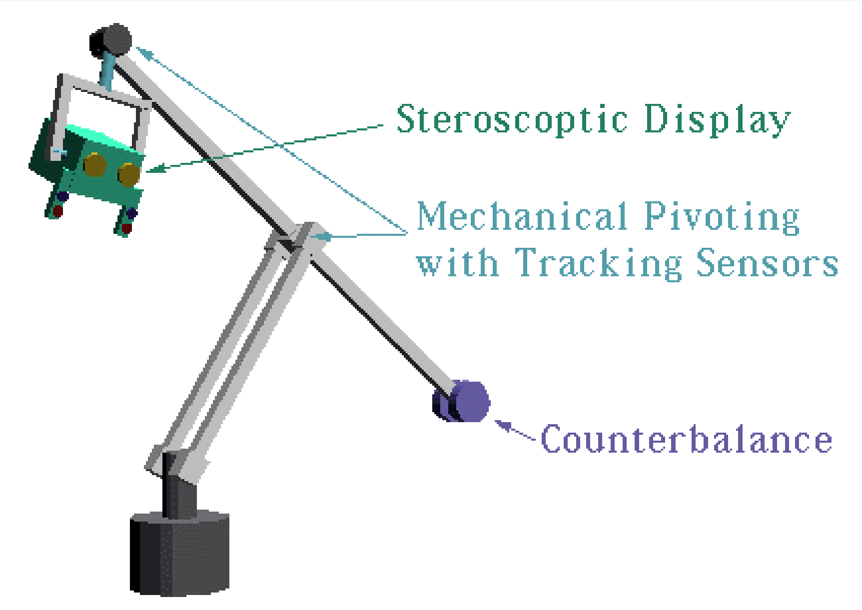
Mechanical Tracking Systems

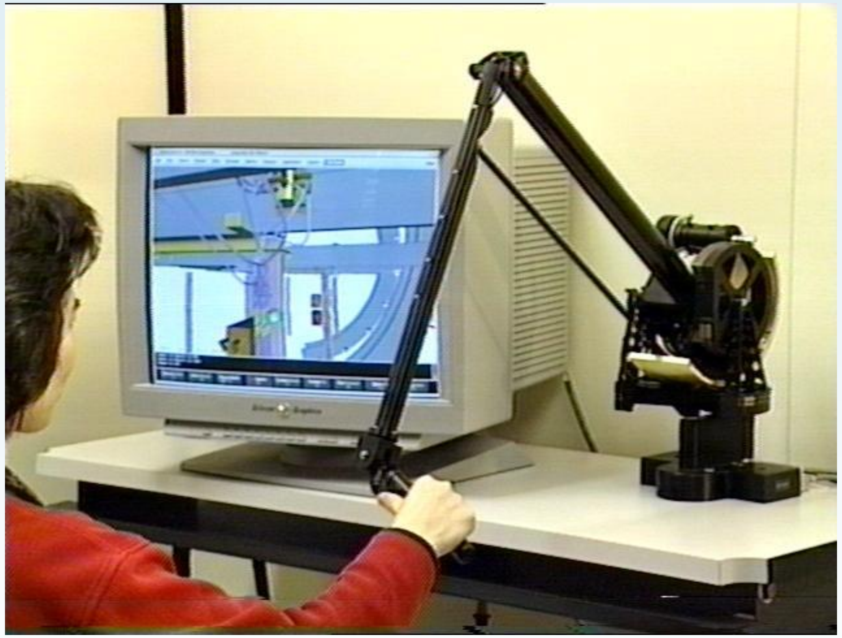
- Tracker consists of a set of rigid mechanical links and joints
- The joint angles are measured using very accurate encoders
- Forward kinematics is used to work out the position and orientation of the display



“Sword of Damocles”

From “Head Mounted Display”

Mechanical Trackers



Sensable Technologies
PHANToM

FakeSpace Boom

Crane-Based Tracking in Film and TV

From http://myemail.constantcontact.com/Egripment-Supports-Virtual---Augmented-Reality.html?soid=1114999858173&aid=z7cLRQiipY8

Crane-Based Tracking in Film and TV

[Mo-Sys e-Crane with StarTracker at Plazamedia (Germany)]

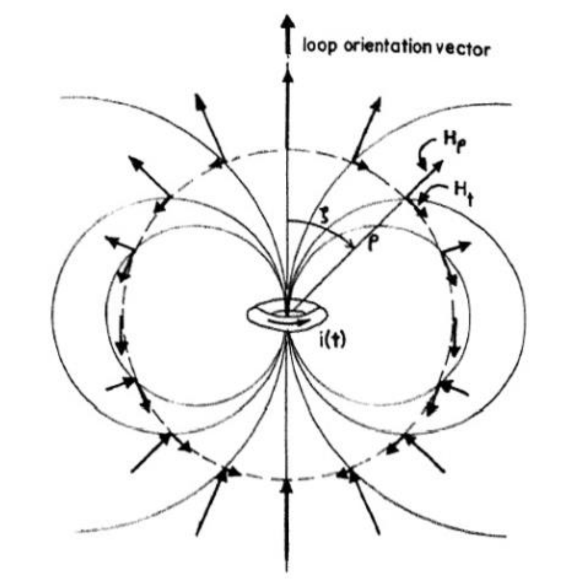
Mechanical Trackers

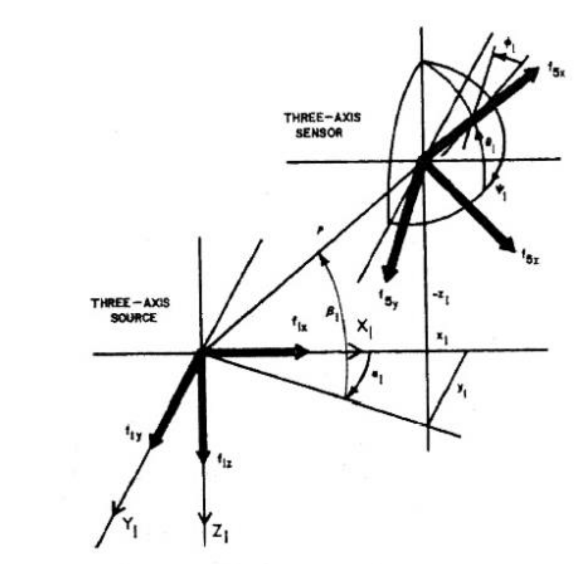
- Advantages:
  - Very accurate, low latency tracking with no drift
  - Offloads most of the weight from a user

- Disadvantages:
  - Can be very cumbersome to setup and use
  - Can limit the volume in which users operate

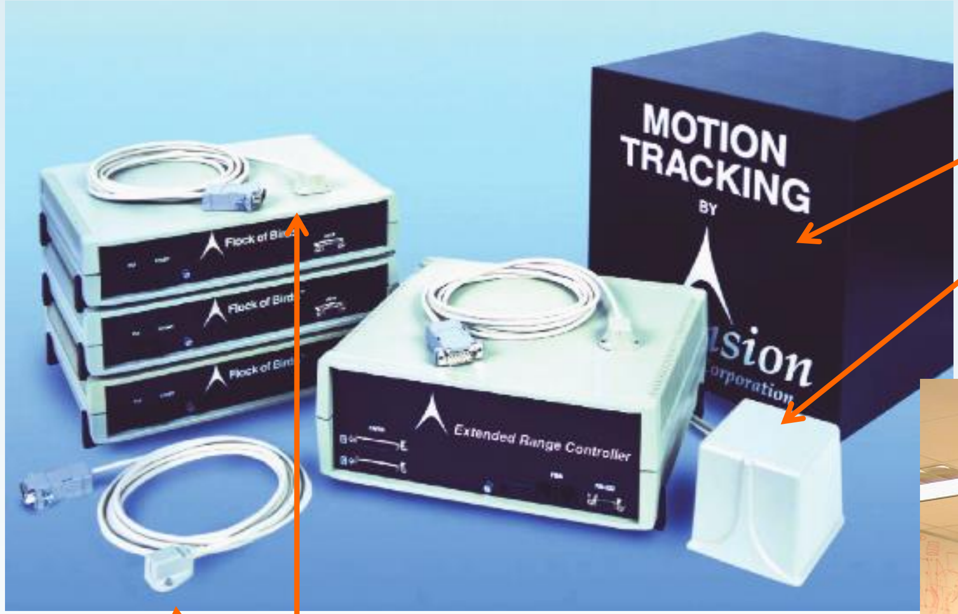
Magnetic Trackers

- A transmitter “pulses” a set of coils and generates 3 orthogonal magnetic fields
- A receiver measure the response of each field in three receiver coils
- The nine measurements are combined to work out position and orientation



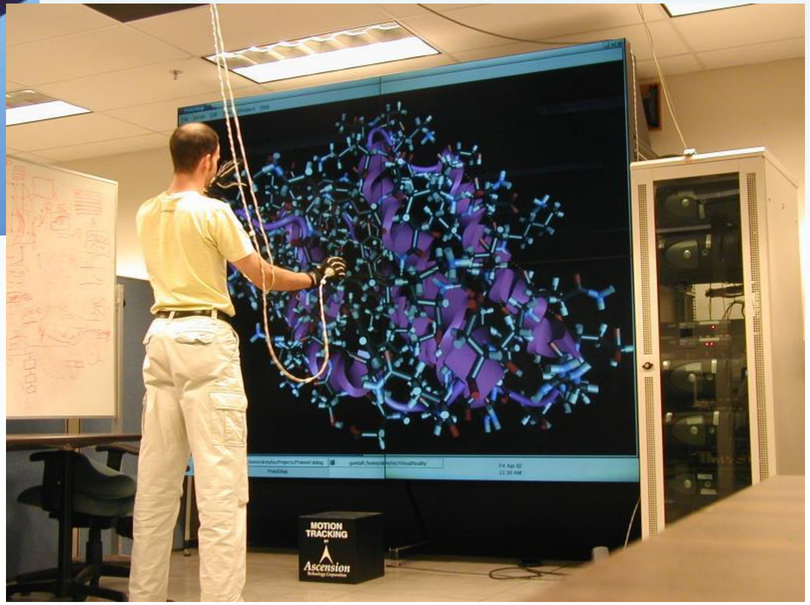


Magnetic Tracker



Transmitters

Receivers



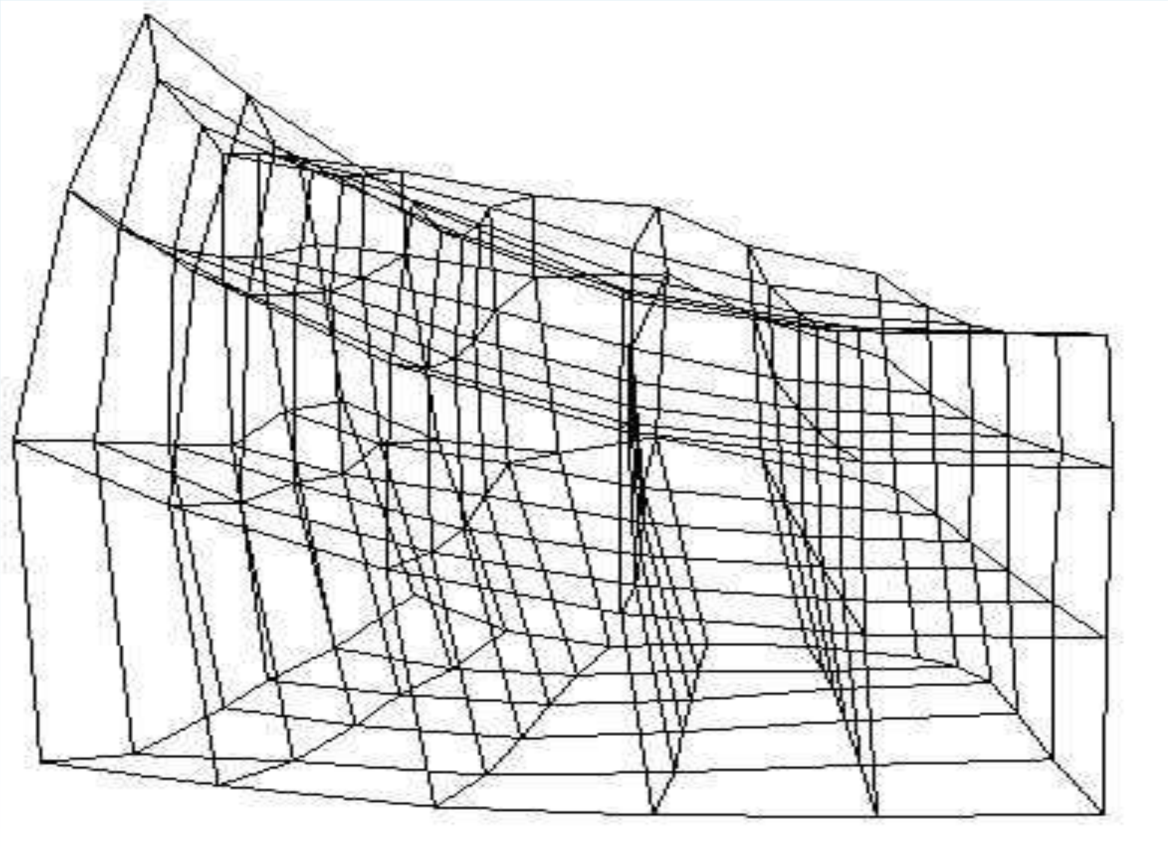
Magic Leap 1

Pico Neo2 Magnetic Tracking

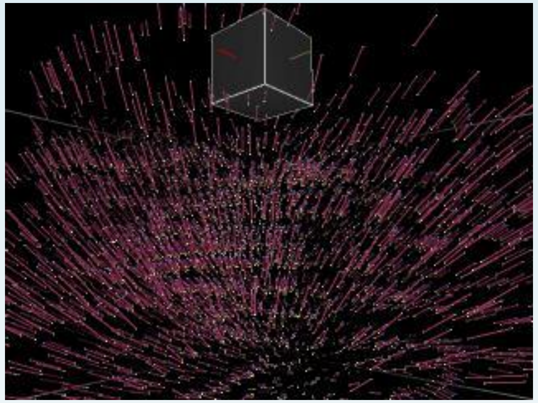
From [Electromagnetic Anti-Occlusion Tracking For Pico Neo 2 – UploadVR @ CES]()

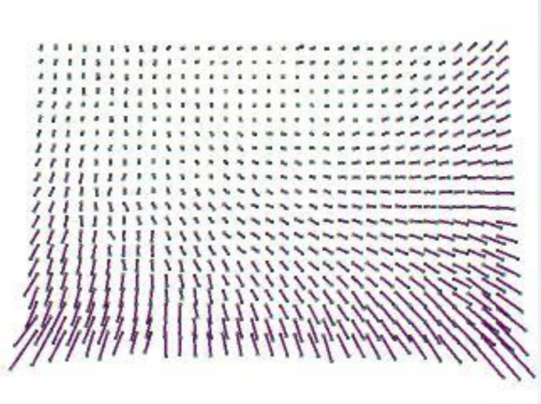
Magnetic Trackers and Spatial Distortion

- Real environments contain metal
- These can distort the magnetic field
- In turn, these can massively distort the output from the tracking system



Calibrating Spatial Distortion





- To sort out the distortion, calibration maps have to be constructed
- Move the sensor through lots of known positions and measure the error

Magnetic Tracking Systems

- Advantages:
  - Sensor can be small, lightweight and low power
  - Does not require line-of-sight

- Disadvantages:
  - Problems with sensor performance and accuracy caused by distortion of the magnetic field
  - Limits on the update rate

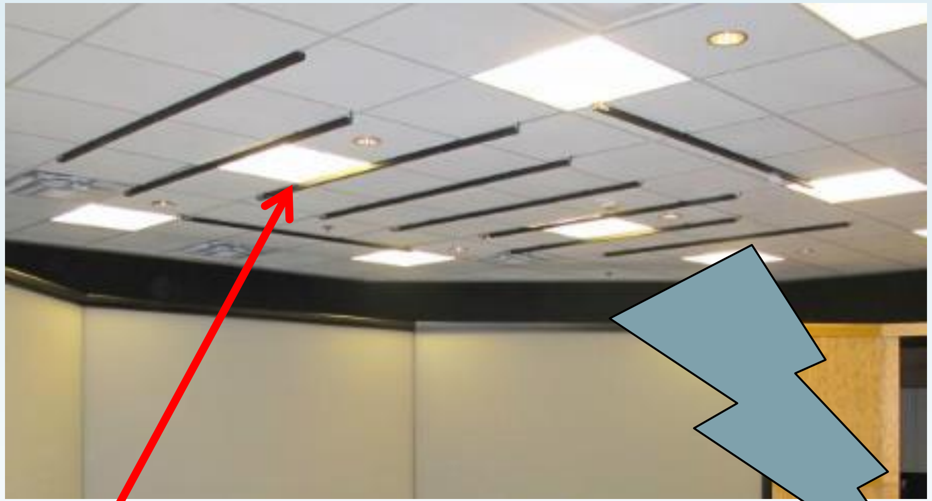
Acoustic Trackers

- Uses sound waves for transmission and sensing
- Ultrasound broadcast and time-of-flight until reception used to compute range
- Mostly outside-In (microphone sensors)
- Logitech Acoustic Tracker
- Samba De Amigo Maracas)

Logitech Acoustic Tracker

Dreamcast maracas controllers for “Samba De Amigo”

InterSense IS 900



Acoustic signal

Command to broadcast pulse

Figure 2 – IS-900 Processor

Time of Reception

Acoustic Sensors

- Advantages:
  - Very simple way to provide absolute distance measurements
  - Lightweight low-cost sensors

- Disadvantages:
  - Can be strongly affected by temperature and humidity
  - Can be strongly affected by ambient noise (e.g., keys jangling)
  - Limited update rate due to reverberation

Current Tracking Systems

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Main Types of Tracking Technology

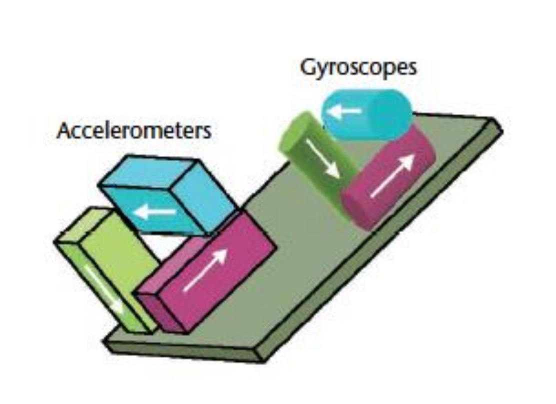
- Mechanical
- Magnetic
- Acoustic

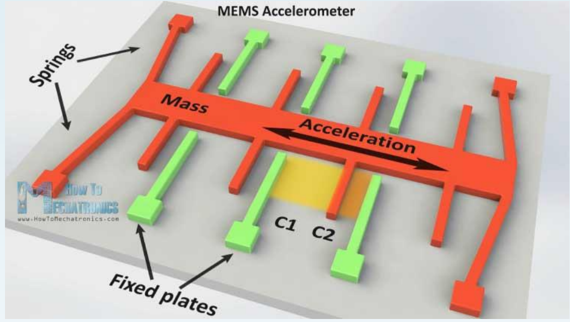
Historically important, niche use today

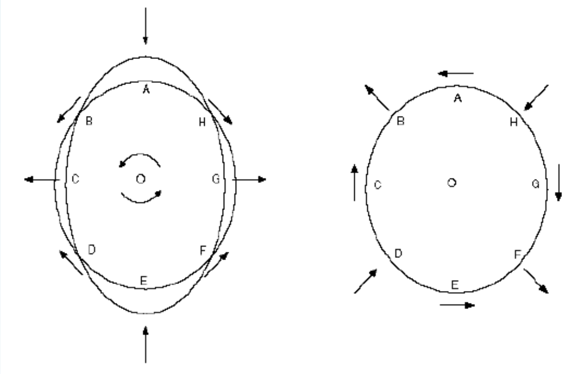
- **Inertial**
- **Optical**
- **Hybrid**

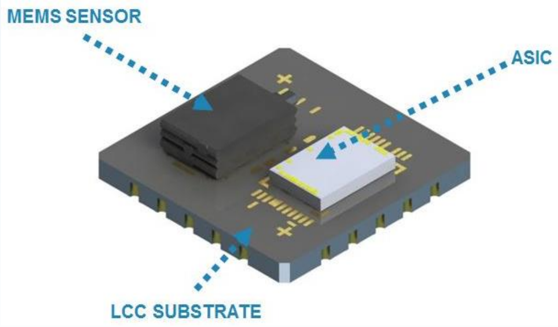
Very widely used

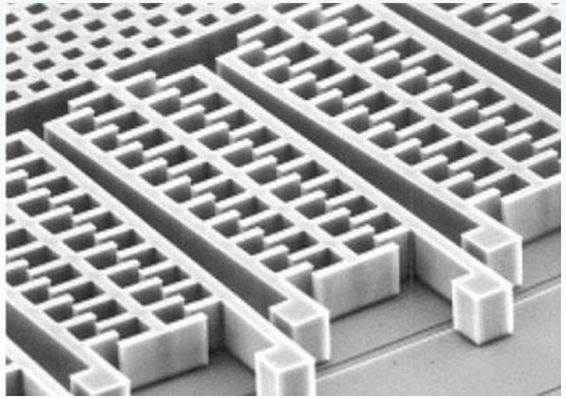
Inertial Trackers (IMUs)

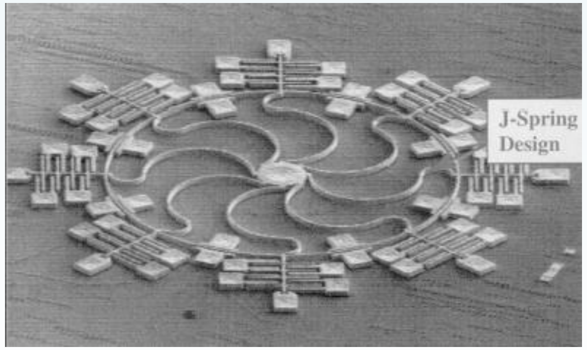




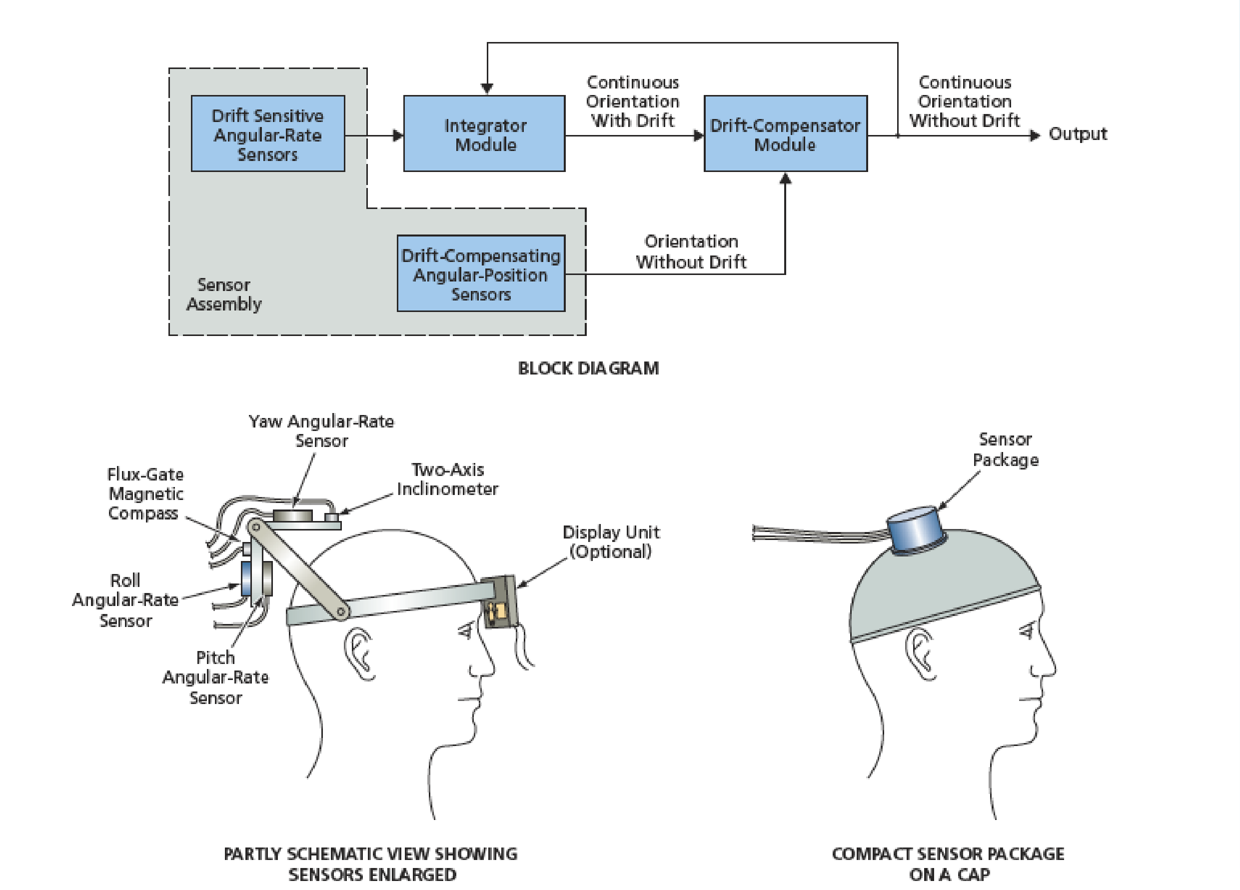








IMU-Based Head Tracking



From “[Inertial Orientation Trackers With Drift Compensation]”

Samsung Gear + Other 360 Videos

Xsens Motion Capture Suit

Really Big Strapdown IMUs

High Quality Inertial Tracking

[Mo-Sys - GyroTracker and VizRt at Red Bull Air Race in Budapest (June 2015)]

IMUs and Drift

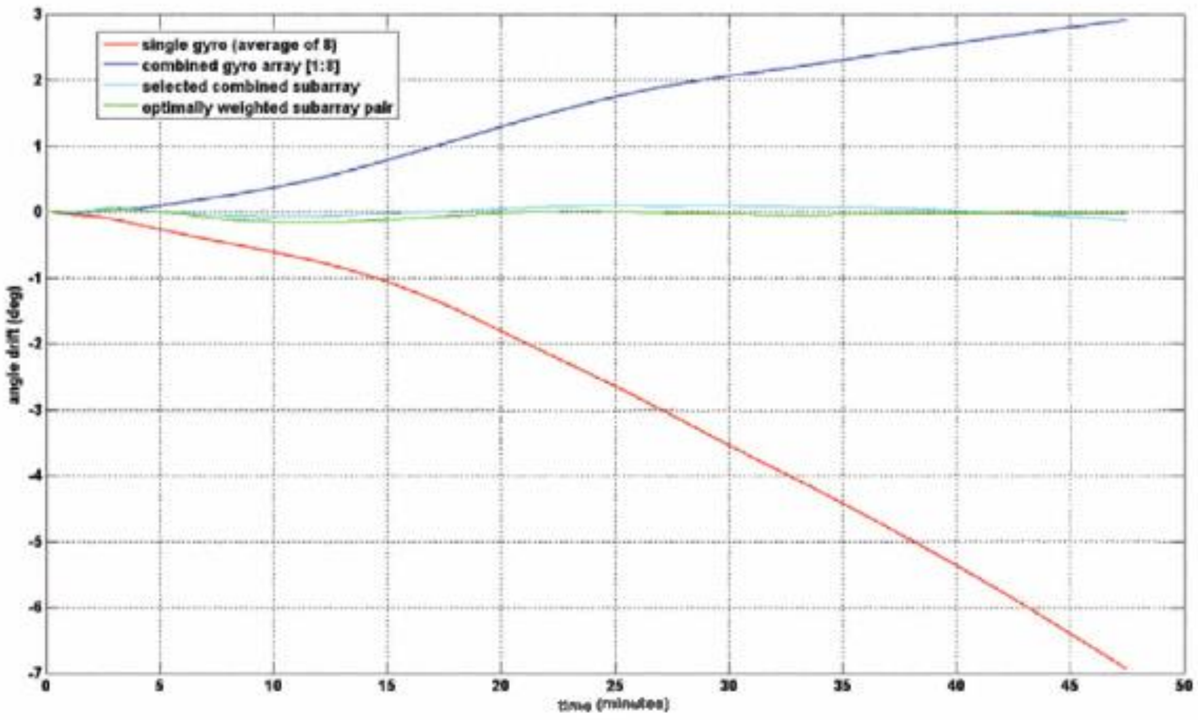
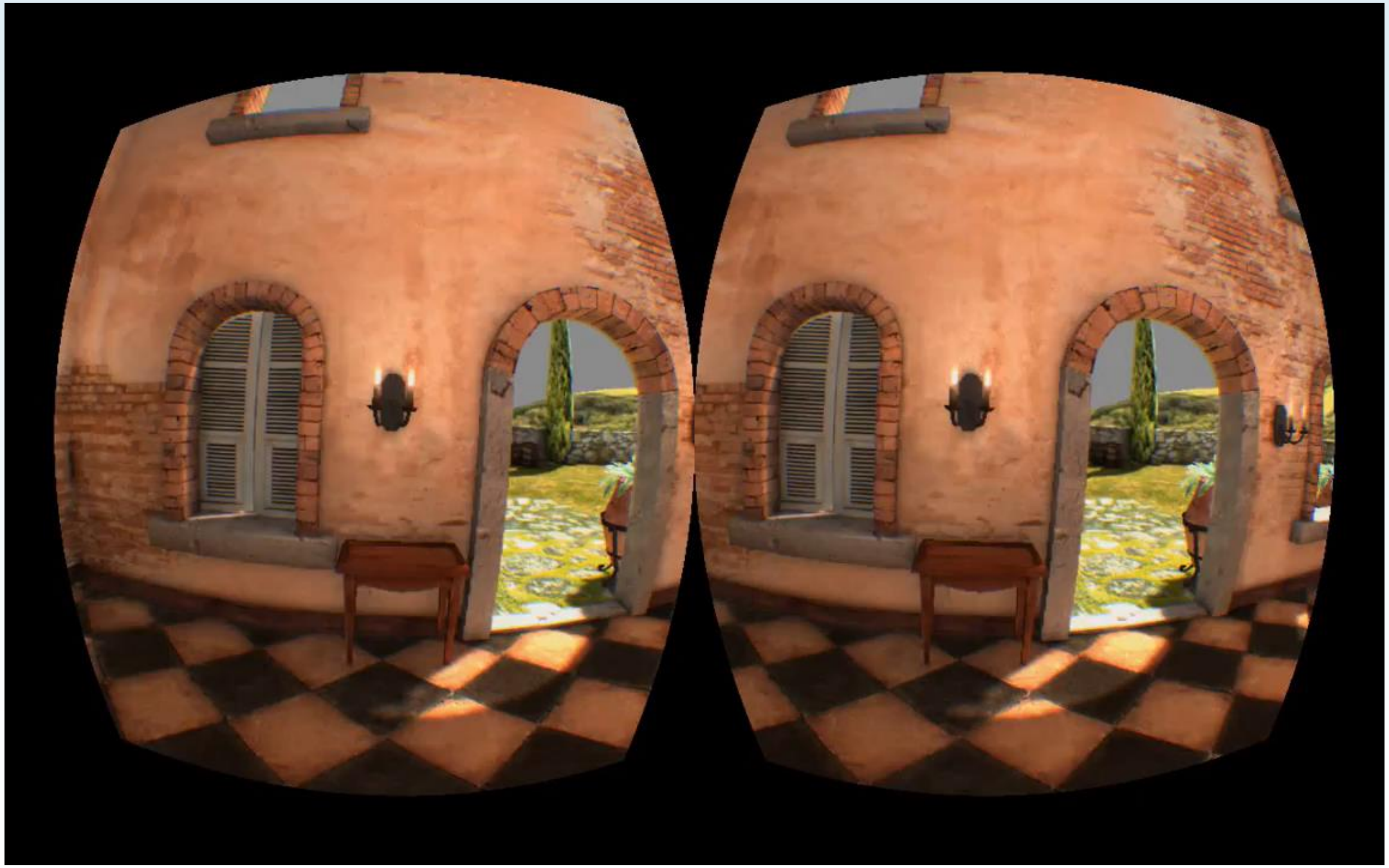


Figure 4. Mean angle drift comparison

From [“Miniature IMU/INS with optimally fused low drift MEMS gyro and accelerometers for applications in GPS-denied environments”]

Low Quality (and Broken!) Inertial Tracking



See “The accuracy of the Oculus Rift virtual reality head-mounted display during cervical spine mobility measurement” by Xu for a recent analysis

Trying to Use IMUs to Estimate Position

From “Pure IMU Position Tracking is a No-Go”

Issues with Magnetometer / Accelerometers

- Magnetometers suffer from noise just like magnetic sensors

- Accelerometers only provide tilt information when stationary
  – Can be a long time between events happening
  – Can suffer from noises and biases

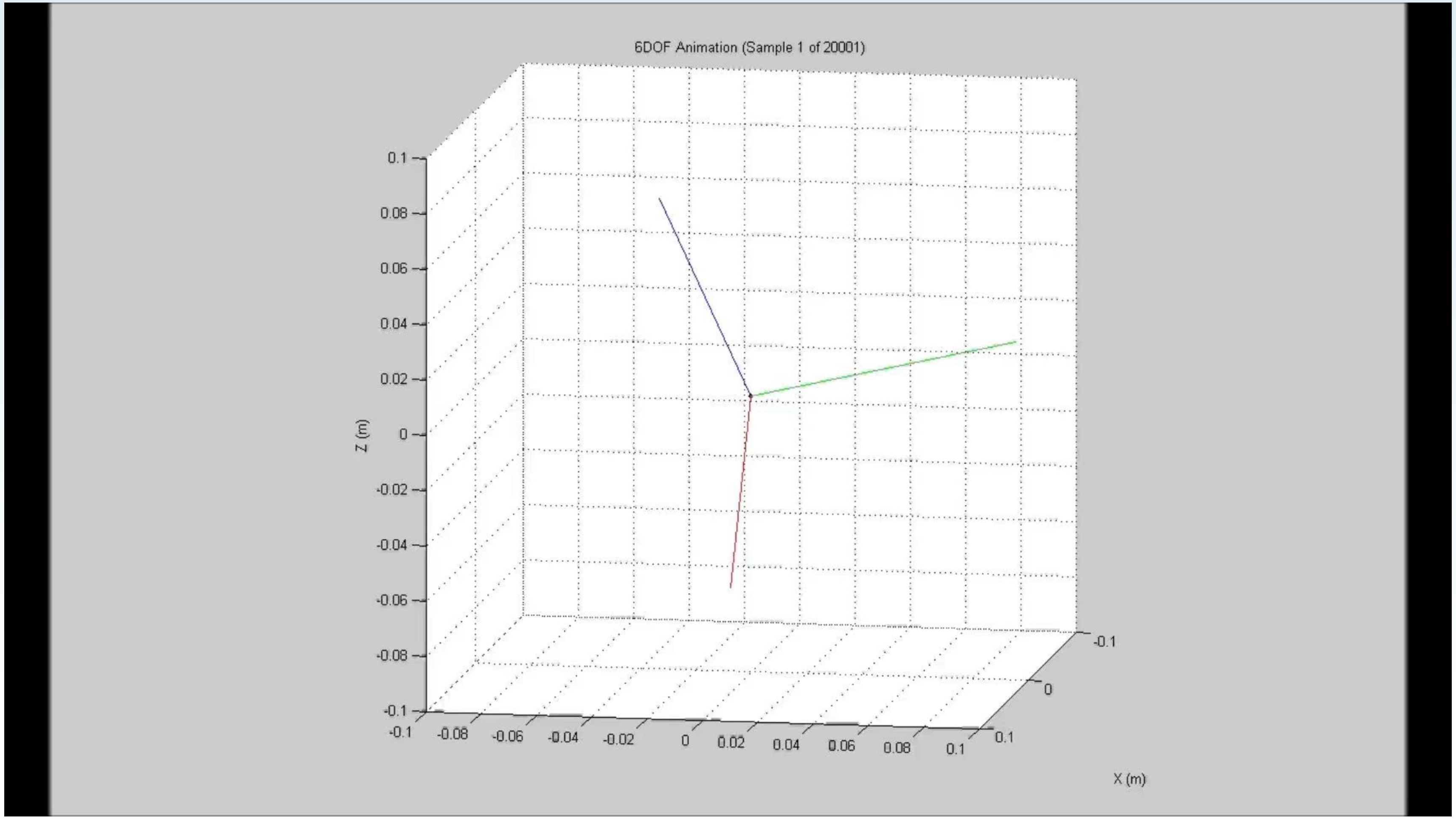
- However, in some cases we can use clever techniques to make them work better

Clever Inertial Tracking

- Foot mounted IMUs use the facts that the foot is stationary half the time

- Huge reduction in drift from metres per minute to metres per hour

Foot Mounted IMU



[3D Foot Tracking with IMU]

Advantages and Disadvantages

- Advantages:
  - Sourceless and self-contained
  - Low power
  - High update rate

- Disadvantages:
  - Suffers from drift except in very special cases
  - Uses other sensors to correct, but these can suffer from distortion and error

Optical Tracking Systems

- Optical tracking systems are uniquely flexible
- They can be inside-out or outside-in
- They can estimate just position, or position and orientation
- They can track a single feature or multiple features

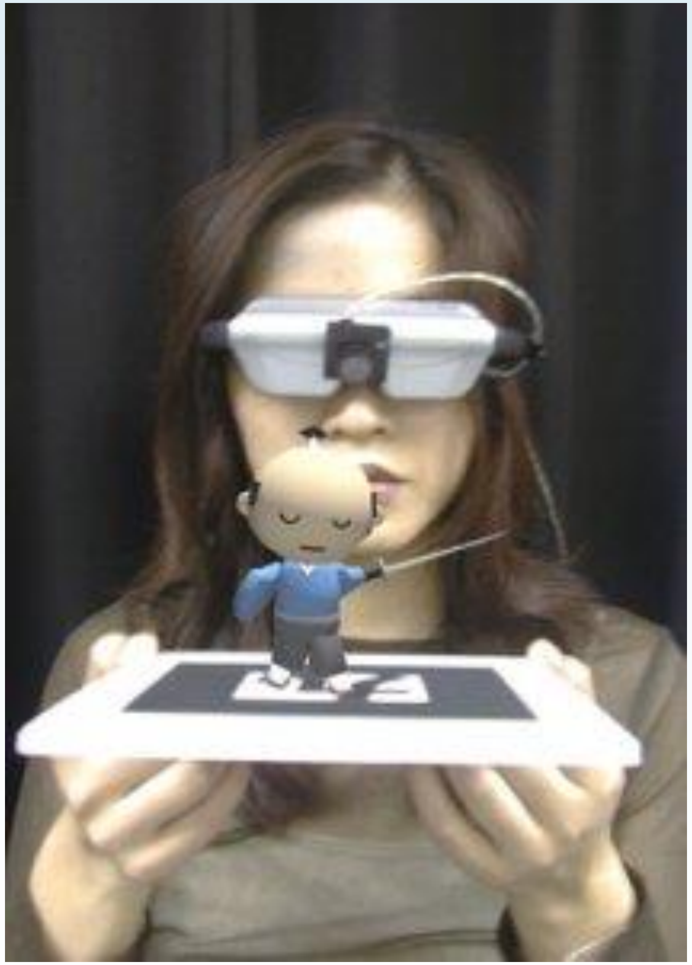
Types of Optical Tracking Systems

- Single camera (head) tracking:
  - Fiduciary marker-based
  - Coded marker-based
  - Natural landmark (SLAM) based

- Whole body:
  - Specialised optical markers
  - Depth Cameras

2D Fiduciary Markers

- Until the release of ARKit / ARCore, the most widely used system
- Markers are 2D rectangles with distinctive patterns
- The pose of the pattern is computed relative to the camera



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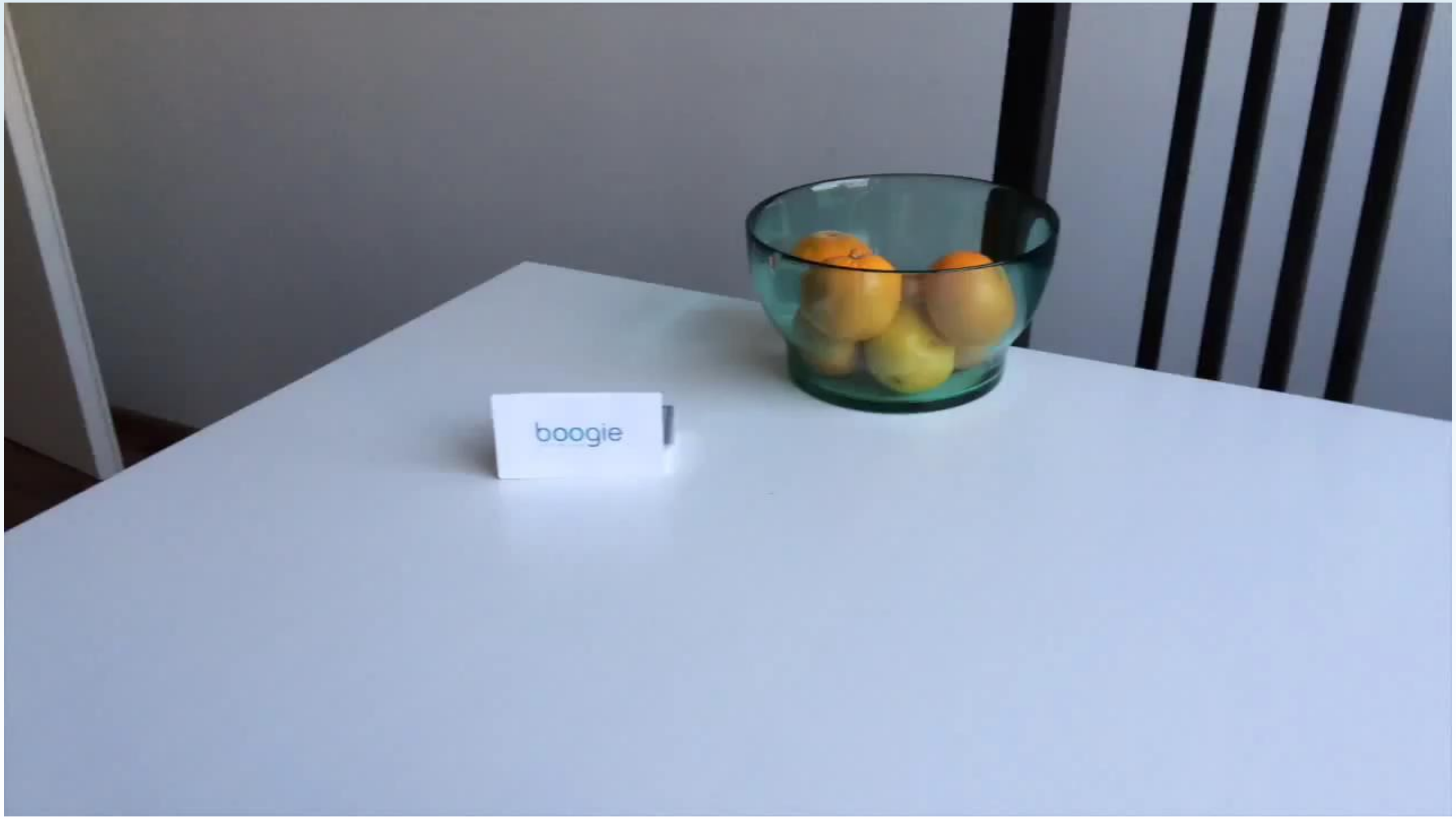
2D Feature Matching

Tabletop AR



Vuforia + Unity3D Augmented Reality Demo - Ninja and Bear fighting,
https://www.youtube.com/watch?v=cTIjpo6cb6M

Vision Target Tracking on Buildings

From “Visualizing Heritage with Augmented Reality”, J. Lin, MScCGVI 2019

Fiduciary Markers

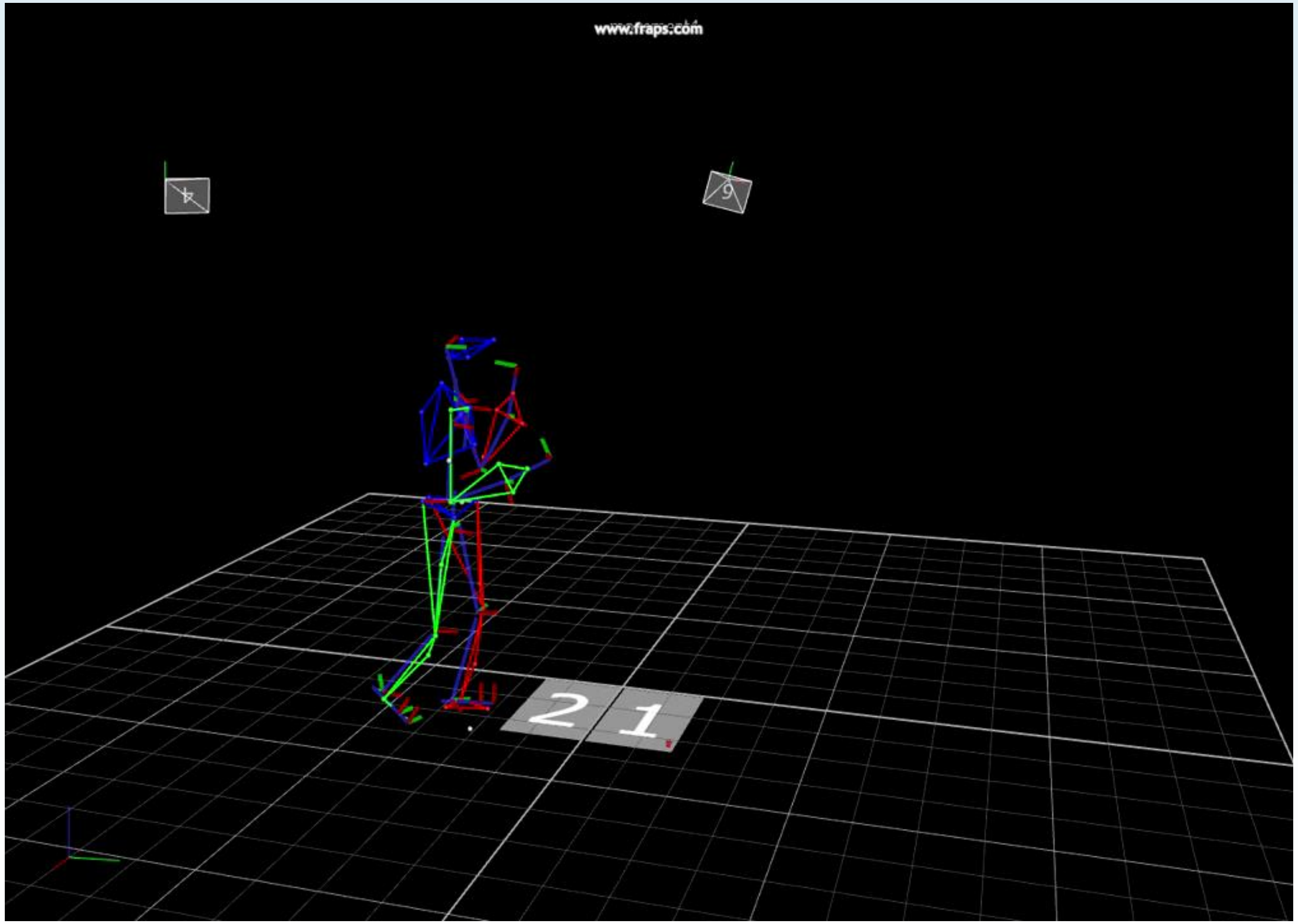
- Advantages:
  - Works well in small environments
  - Aligns graphics with known objects (e.g., magazines)
  - Very well known computer vision theory
  - Mature commercial systems

- Disadvantages:
  - Only works when close to target and almost looking head on
  - Requires careful choice of texture and location from which the target feature image was captured

Optical Trackers

- Measures reflected or emitted light
- Involves a source (active or passive) and sensor
- Sensors can be analogue or digital
- Photo sensing (light intensity) or Image forming (CCD)
- Triangulation with multiple sensors
- Possible to be both outside-in and inside-out

Vicon



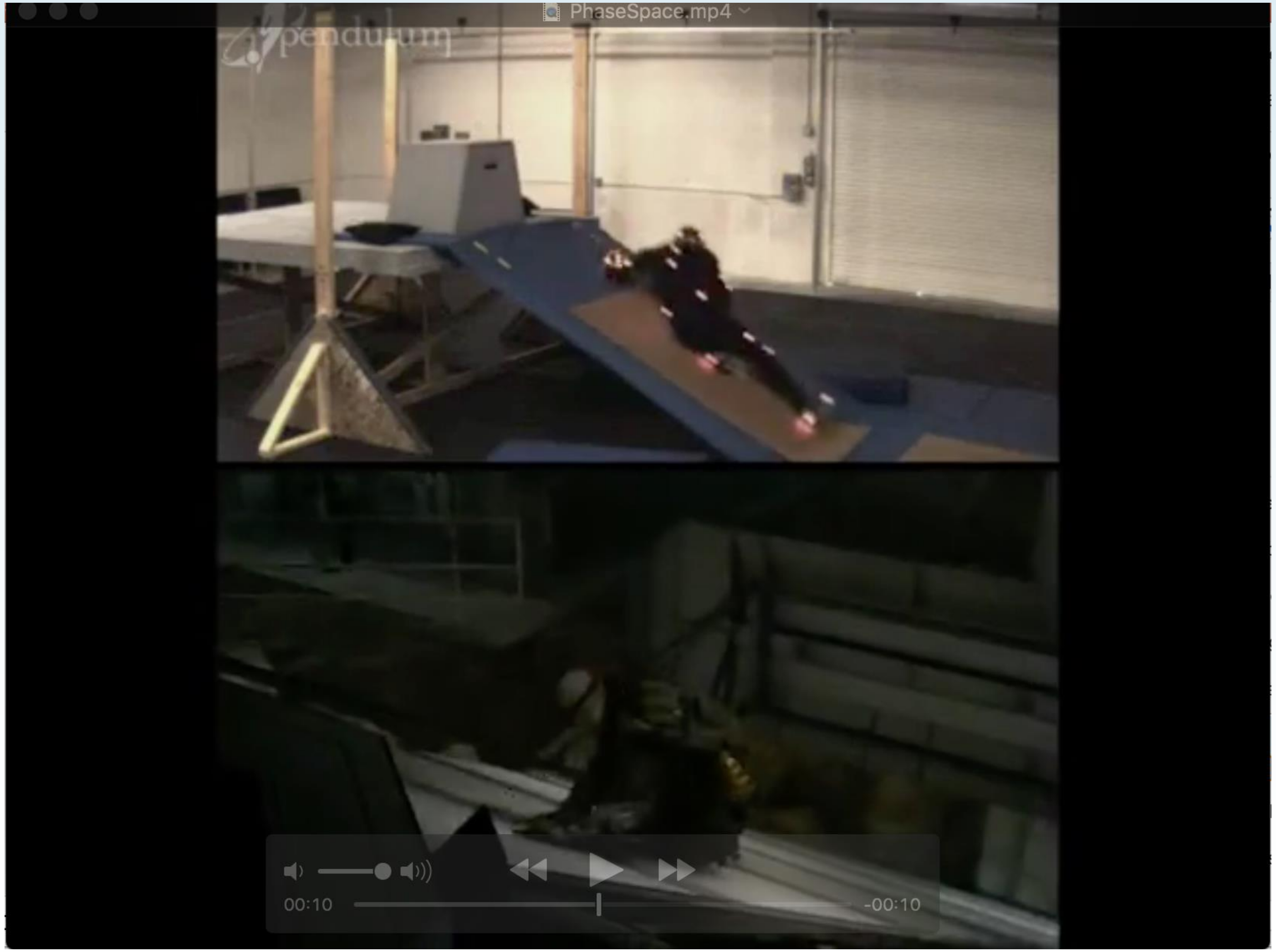
Vicon Failure (Markers Occluded)

Vicon tracking failure due to occluded markers (UCL)

Active Marker Systems

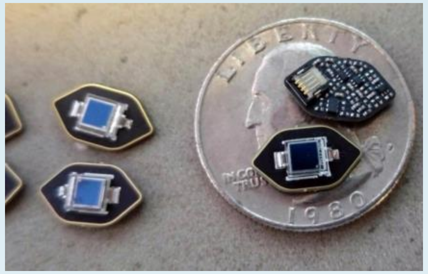
- A problem with the passive marker systems is that all dots look the same
- In active marker systems, all dots broacast an ID code and can be uniquely identified

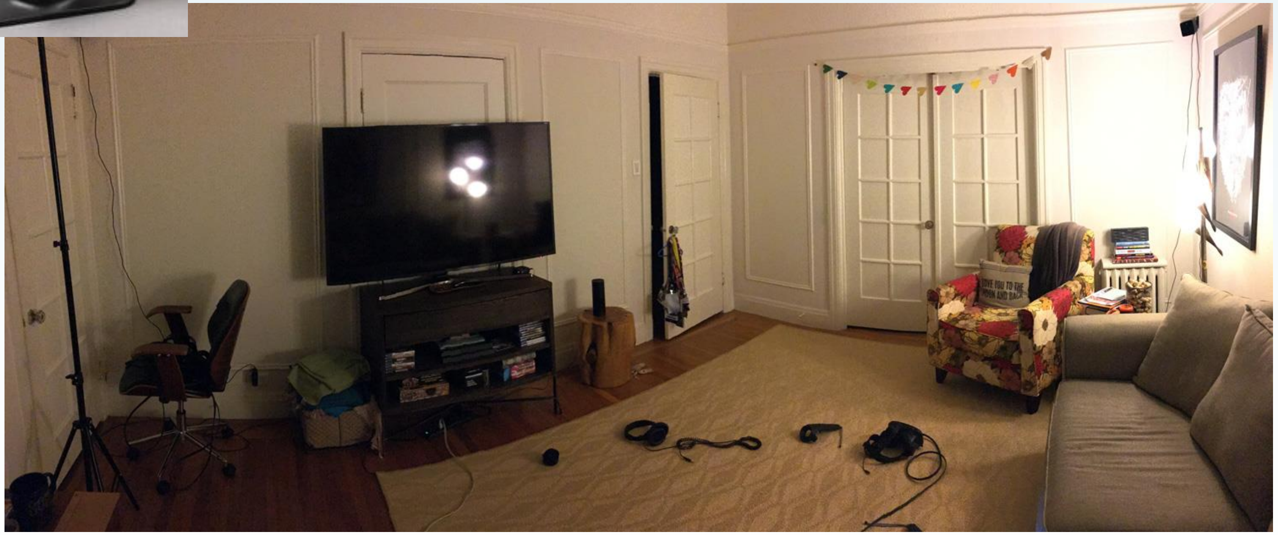
Demo Reel (PhaseSpace)



[PhaseSpace]

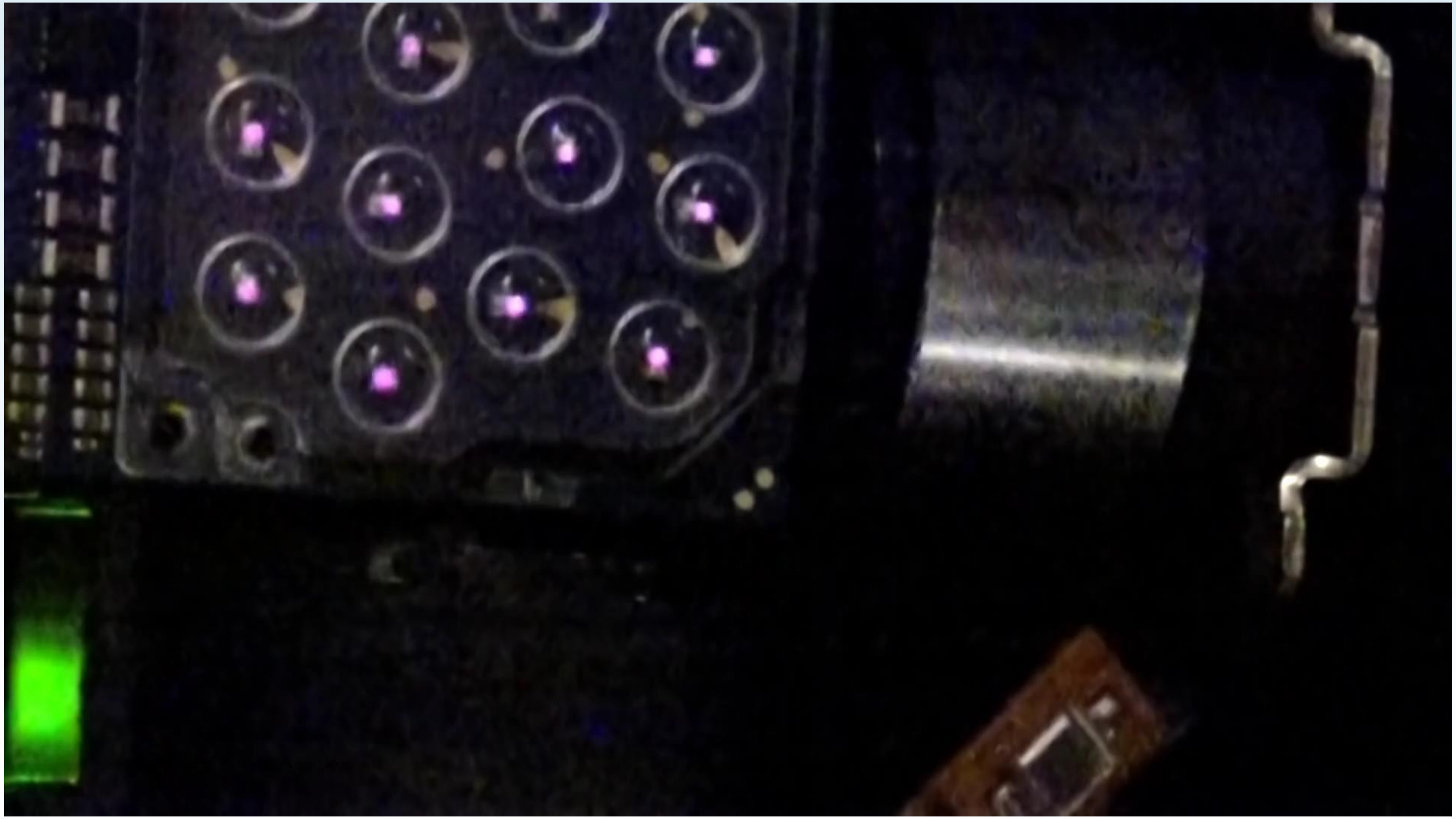
Light Fans





Optical Trackers – Lighthouse

HTC Vive Base Station in Action



From [SteamVR HTC Vive In-depth - Lighthouse Tracking System Dissected and Explored]

Marker-Based Tracking

- Advantages:
  - Extremely accurate
  - Very high update rates
  - Light

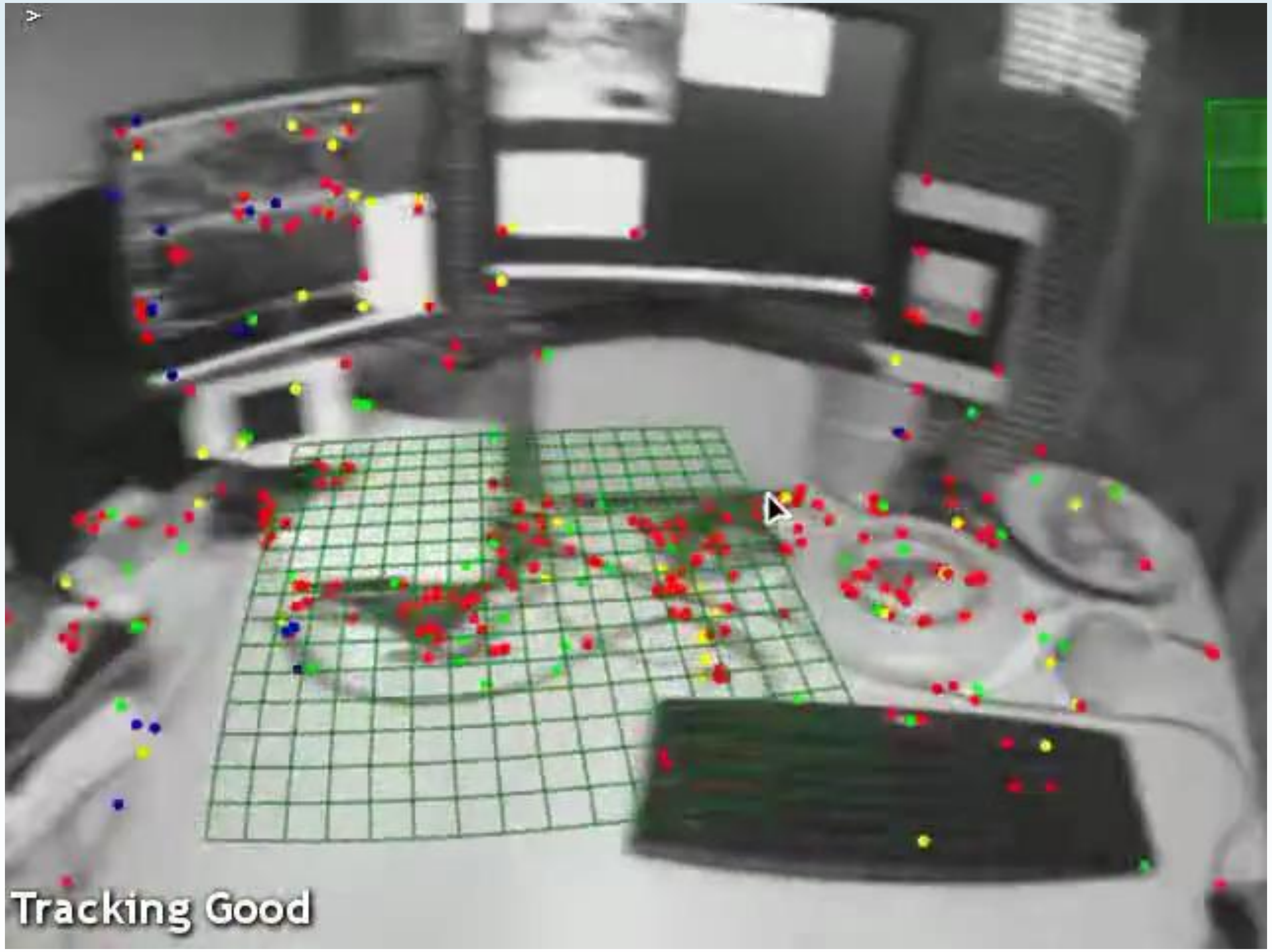
- Disadvantages:
  - Markers can get lost (problem with outside-in systems)
  - Marker identities can become swapped (causing tracker failures)
  - Can be troublesome to put on

Natural Landmark (SLAM-Based) Systems

- Rather than manually put markers up in the environment, let the system build its own map of the world

- Use this to work out the position of the camera and work out its position again in the future

Parallel Tracking and Mapping (PTAM)



Parallel Tracking and Mapping for Small AR Workspaces, G. Klein

ORB-SLAM

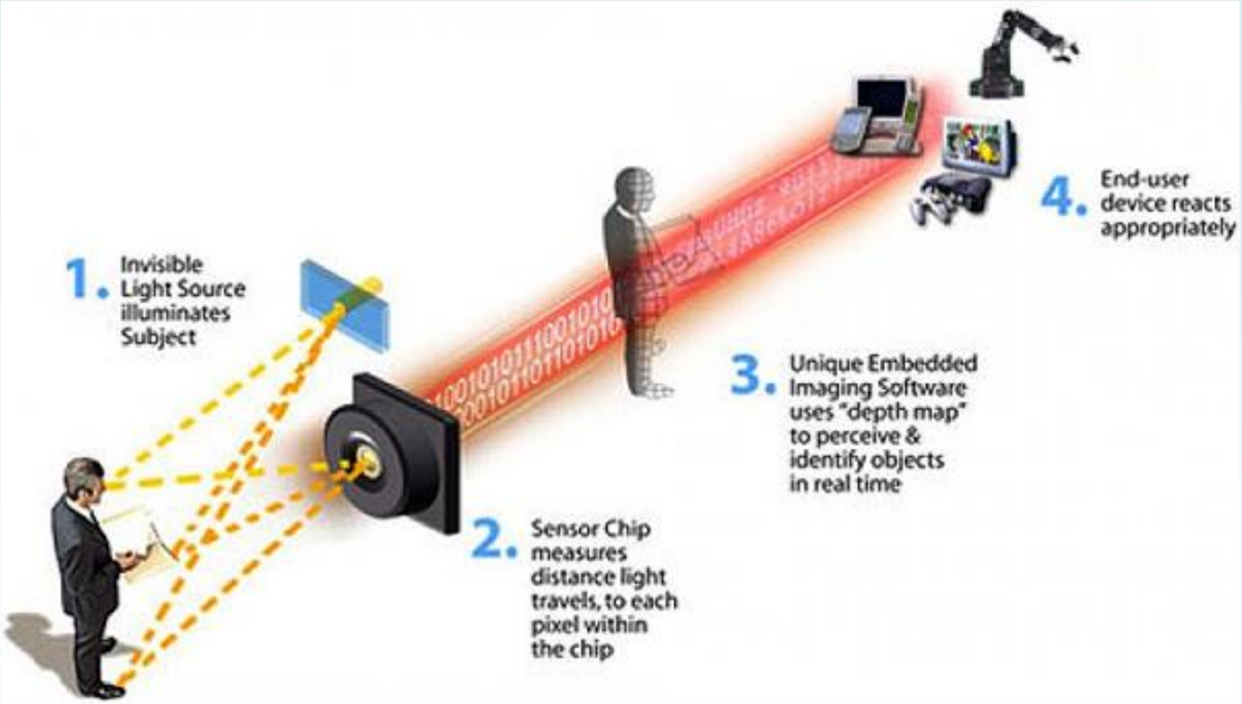
From https://www.youtube.com/watch?v=8DISRmsO2YQ

SLAM-Based Tracking Systems

- Advantages:
  - Do not require markers to be laid out in advance
  - Operating area is almost unbounded

- Disadvantages:
  - Requires relatively heavy computation
  - The map is accurate locally, but will drift globally
  - There can be data association errors in which the system will get lost
  - Systems often keep updating the map, so the results are not repeatable

Depth Cameras



- A special camera illuminates the environment and measures depth directly

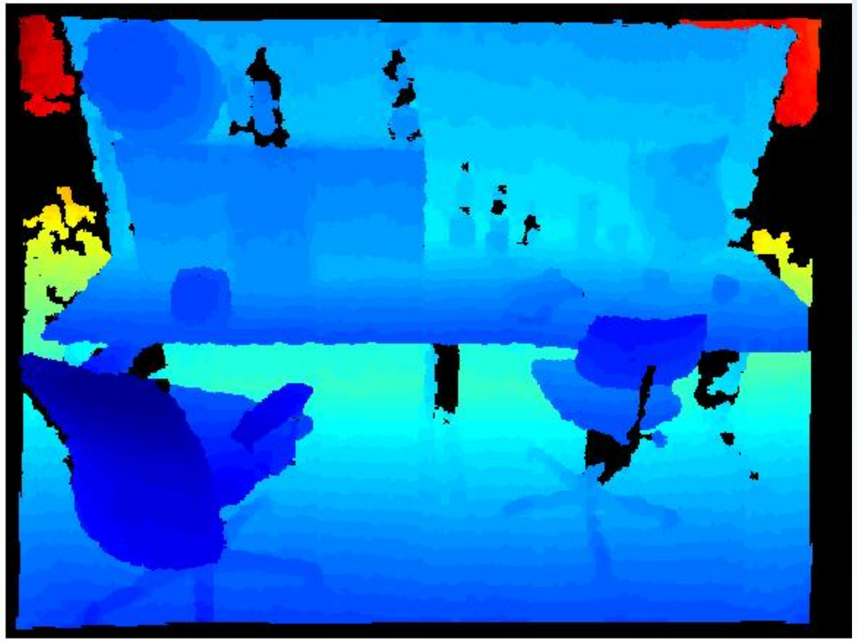
Kinect 1 Structured Light

From [How A Depth Camera from a Kinect Sensor Really Works]

Types of Depth Sensors

RGBD Images

(a) Texture map



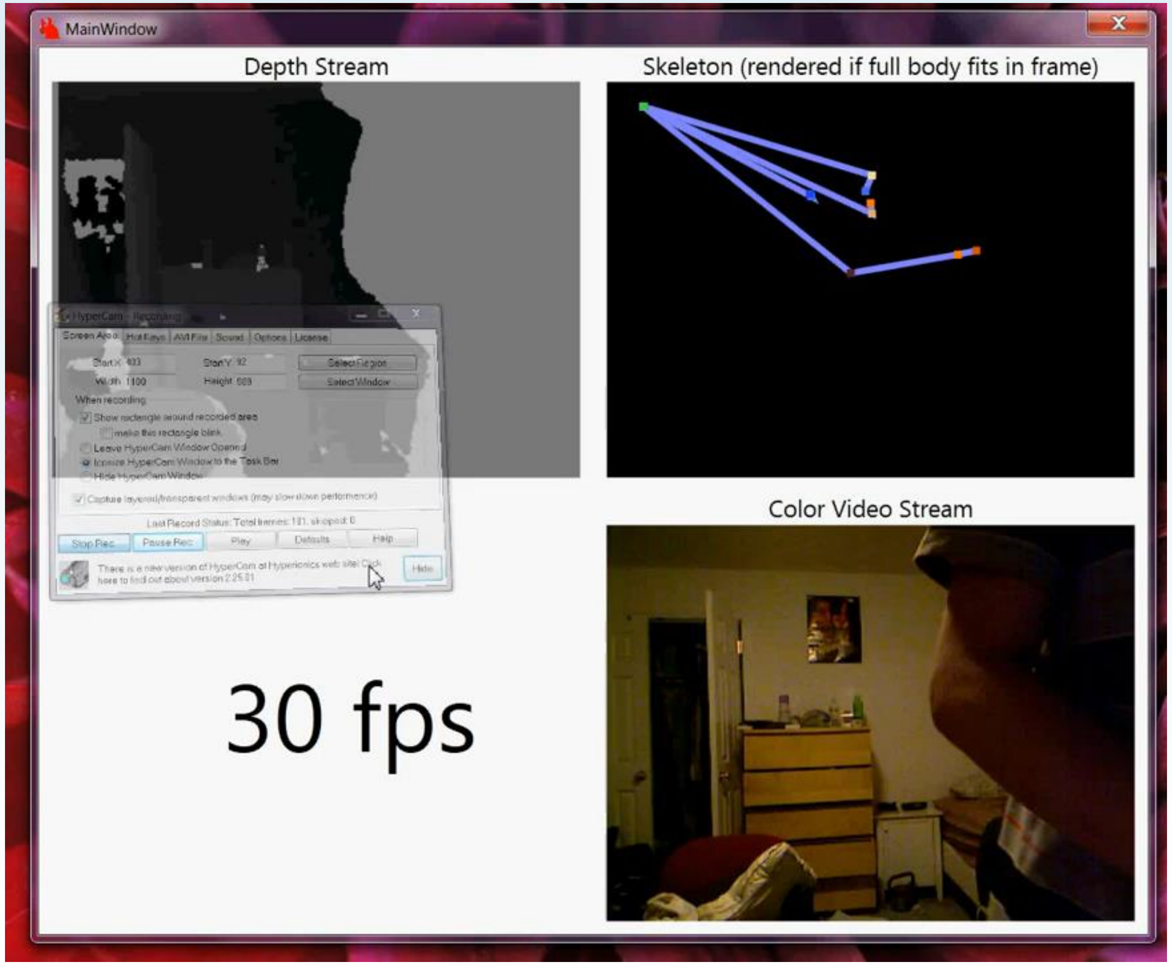
(b) Depth map

From “Local features for RGBD image matching under viewpoint changes”

Depth Image Cameras

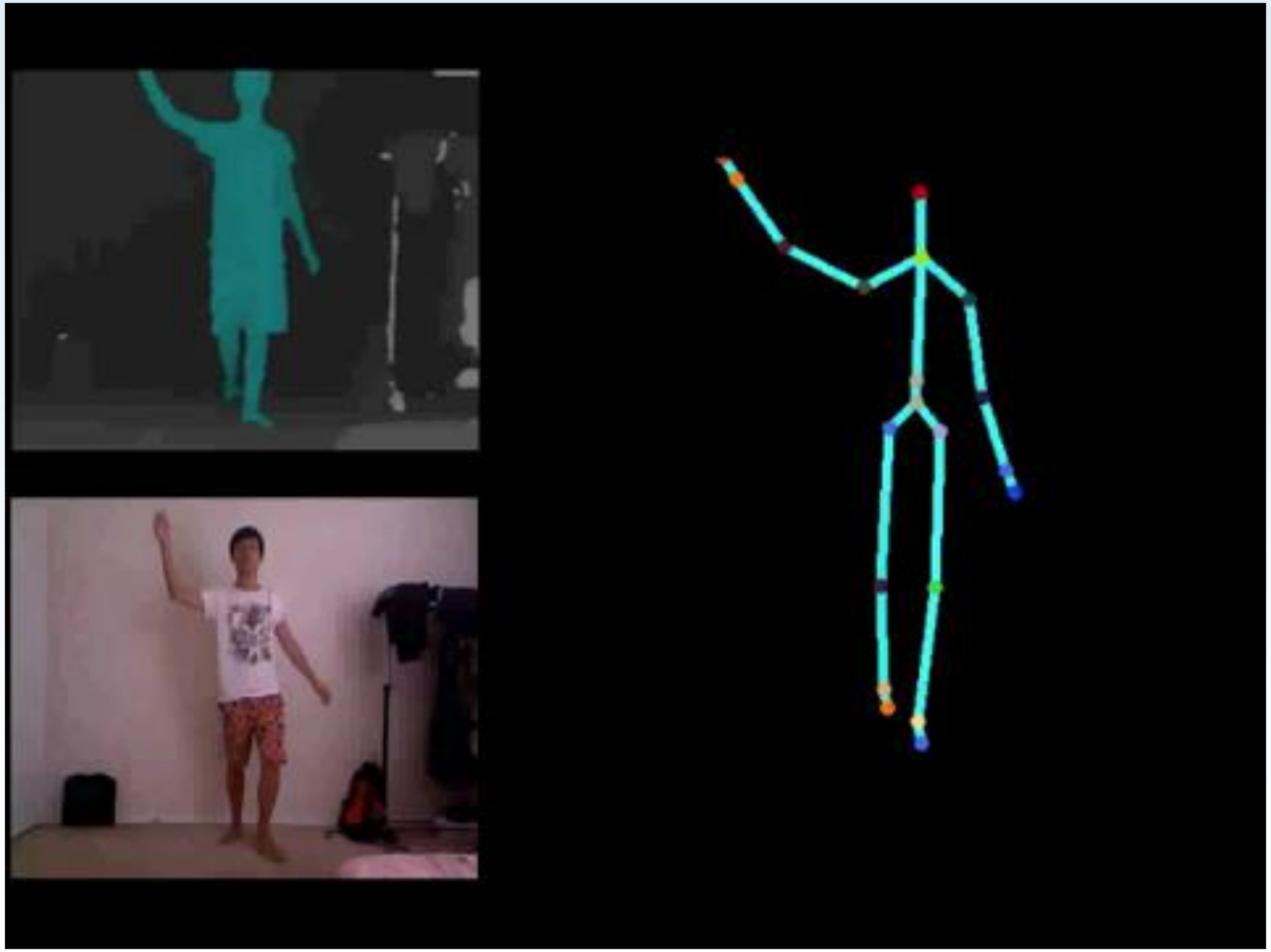
- RGBD camera captures both depth and colour information
- The depth information can be used to construct a 3D skeleton of an object
- This can be used, with gesture recognition, to enable interaction with virtual systems

Kinect with Skeleton Fitting and Tracking



From “Kinect Skeleton Tracker”

Limb Reconstruction Failures



From "Kinect failure examples on self-occlusions"

Depth Cameras

- Advantages:
  - Directly measure range and are fairly accurate
  - Can detect plain objects (e.g., walls)

- Disadvantages:
  - Not terribly accurate

Hybrid Tracking Systems

- *Part 1: Introduction*
  - *Motivation*
  - *Requirements of the Ideal Tracking System*
  - *Types of Tracking Systems*
- **Part 2: Different Tracking Technologies**
  - Legacy Tracking Technologies
  - Current Tracking Systems
  - **Hybrid Tracking Systems**
- *Part 3: Case Studies*
  - *Oculus Rift*
  - *Microsoft HoloLens*
  - *Mobiles Phones (ARKit / ARCore)*

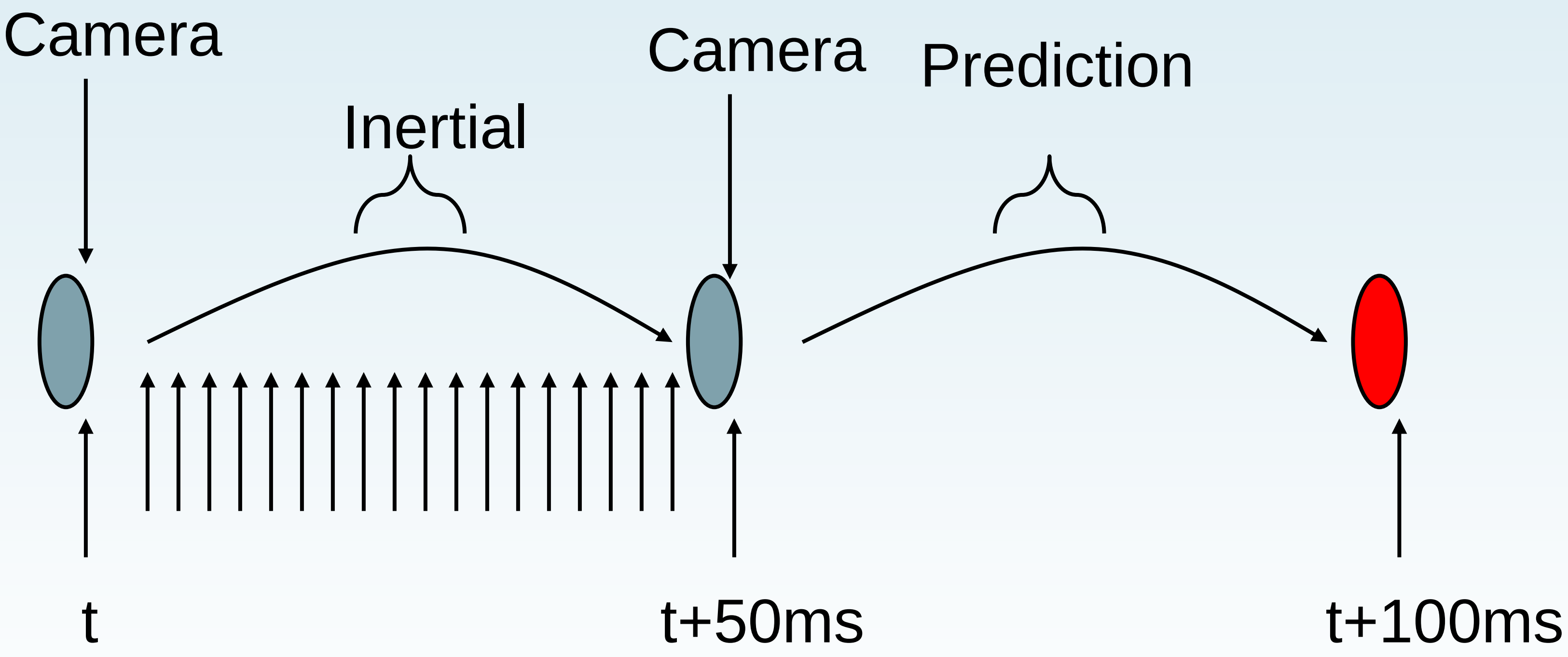
Tracking Systems Today are Hybrid

- Most of the systems we’ve talked about so far have looked at the different components individually
- However, almost all systems today are hybrid - they combine multiple tracking sensors together to leverage the strength of different systems
- The most common approach is hybrid vision / inertial systems

Hybrid Tracking Systems

- Cameras can produce very accurate estimates of position and orientation
- However, they are limited by frame rate and the ability to track something
- IMUs can estimate velocity for short periods of time very accurate with high update rates
- They do not need line-of-sight to any kind of markers
- All current tracking systems are hybrid systems

Fusing Multiple Measurements



Qualcomm Visual-Inertial Odometry

From https://www.youtube.com/watch?v=JshfLAxQAoI

Occulus Quest

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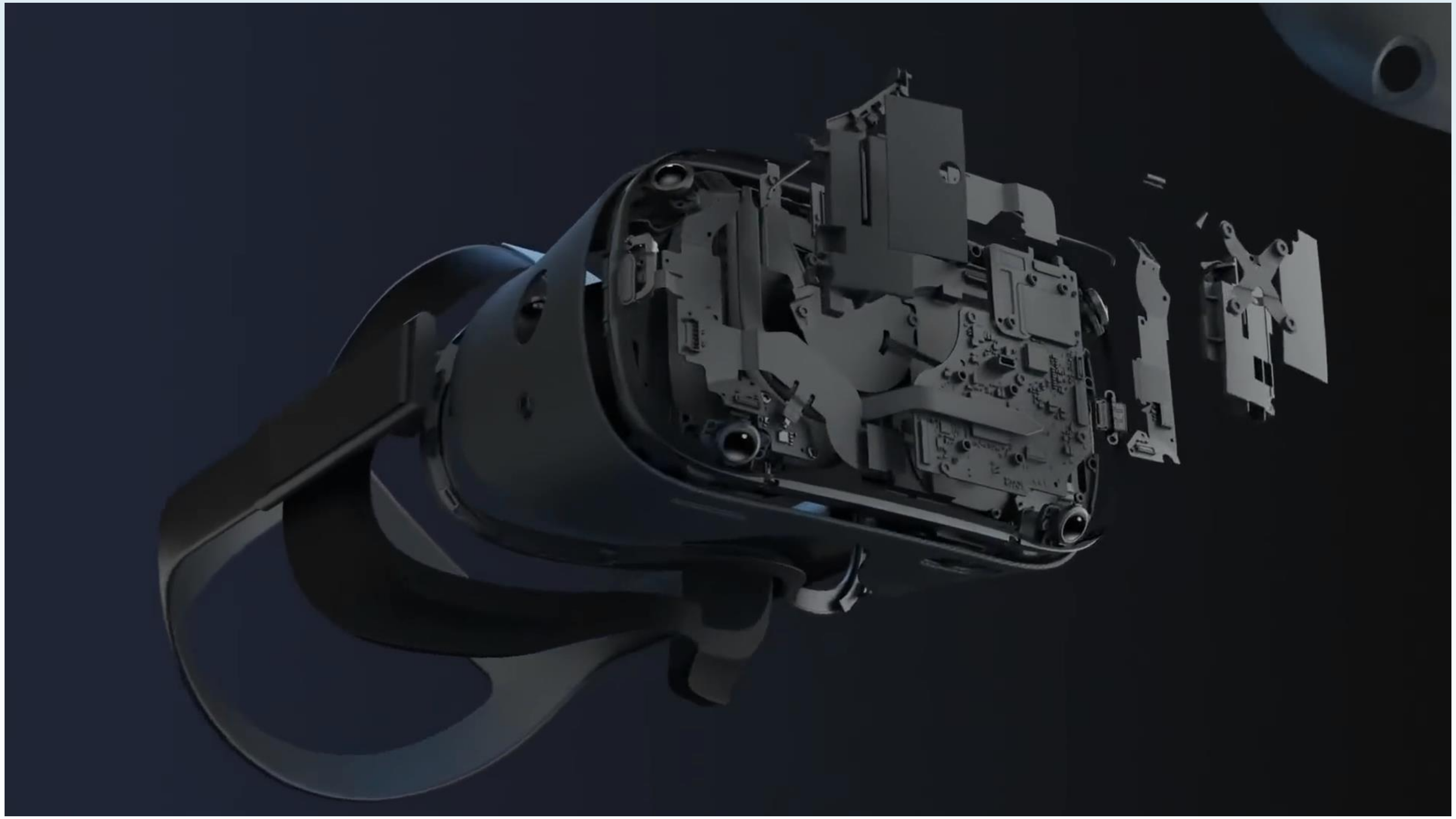
- **Part 3: Case Studies**
  - **Oculus Quest**
  - Microsoft HoloLens
  - Mobiles Phones (ARKit / ARCore)

Oculus Quest

- Released in May 2019
- Low-cost self-contained VR system
- Use a tracking system called Oculus Insight

Oculus Quest Hardware Components



From “Inside Oculus Quest Hardware: Here Are The Sensors Which Track Head And Hand Movement”

Overview of the Quest Tracking System

From [“Oculus Insight: How Facebook’s Oculus Quest & Rift S Track Your Head and Hand Movement”]

Case Studies

- *Part 1: Introduction*
  - *Motivation*
  - *Requirements of the Ideal Tracking System*
  - *Types of Tracking Systems*
- *Part 2: Different Tracking Technologies*
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- **Part 3: Case Studies**
  - **Oculus Quest**
  - Microsoft HoloLens
  - Mobiles Phones (ARKit / ARCore)

HoloLens

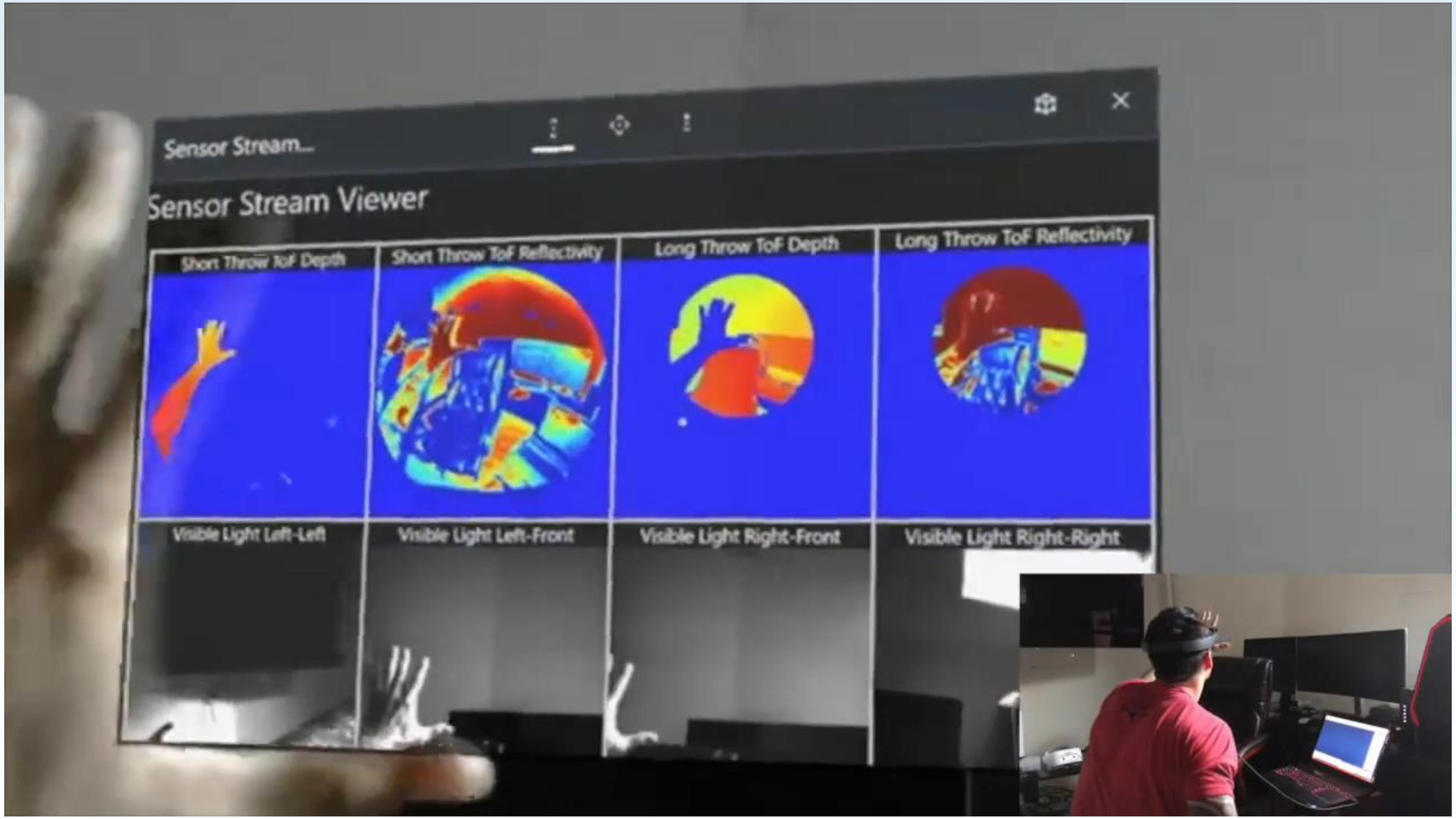
- Released 30 March, 2016
- Self-contained AR system
- Tracking system is hybrid optical inertial SLAM system with spatial mapping and hand gesture tracking

HoloLens Hybrid Tracking System

Sensors

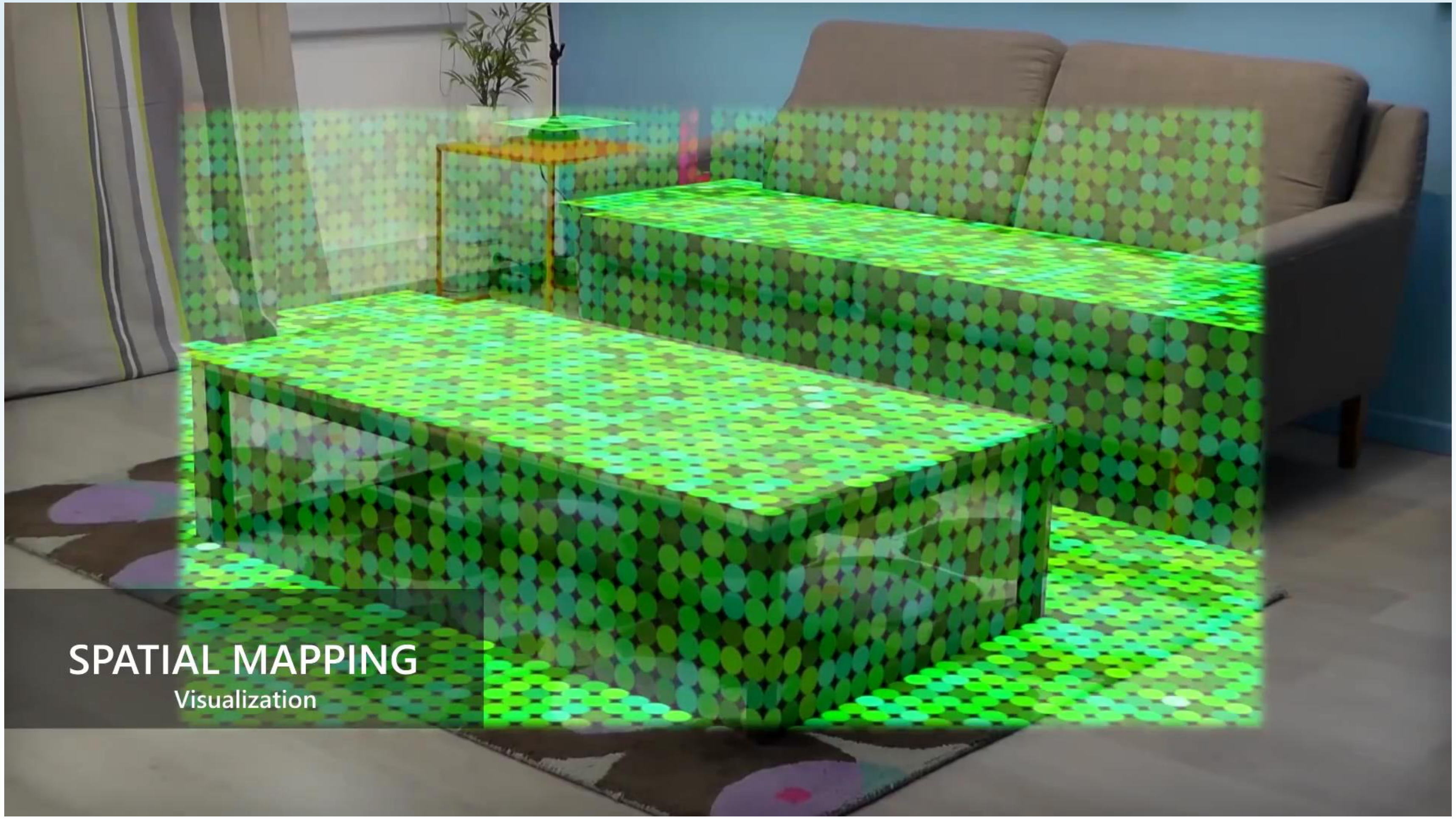
- 1 IMU
- 4 environment understanding cameras
- 1 depth camera
- 1 2MP photo / HD video camera
- Mixed reality capture
- 4 microphones
- 1 ambient light sensor

HoloLens Tracking Sensors



From [“Depth Camera Central Volume 9: Microsoft Hololens Research Mode RS5 Computer Vision Sensor Streams”]

Spatial Mapping



From [“Microsoft HoloLens: Spatial Mapping”]

Mobiles Phones (ARKit / ARCore)

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- **Part 3: Case Studies**
  - Oculus Quest
  - Microsoft HoloLens
  - **Mobiles Phones (ARKit / ARCore)**

ARKit / ARCore

- Mobile phone AR development has been going on since the early 2000s
- Original systems used marker-based tracking but current systems are hybrid inertial optical systems with optional depth cameras
- Mainly implemented in two libraries ARKit (iOS) and ARCore (Android)
- As a result, there are approximately 5 billion AR capable devices
- Most recent systems really push the idea of scene understanding

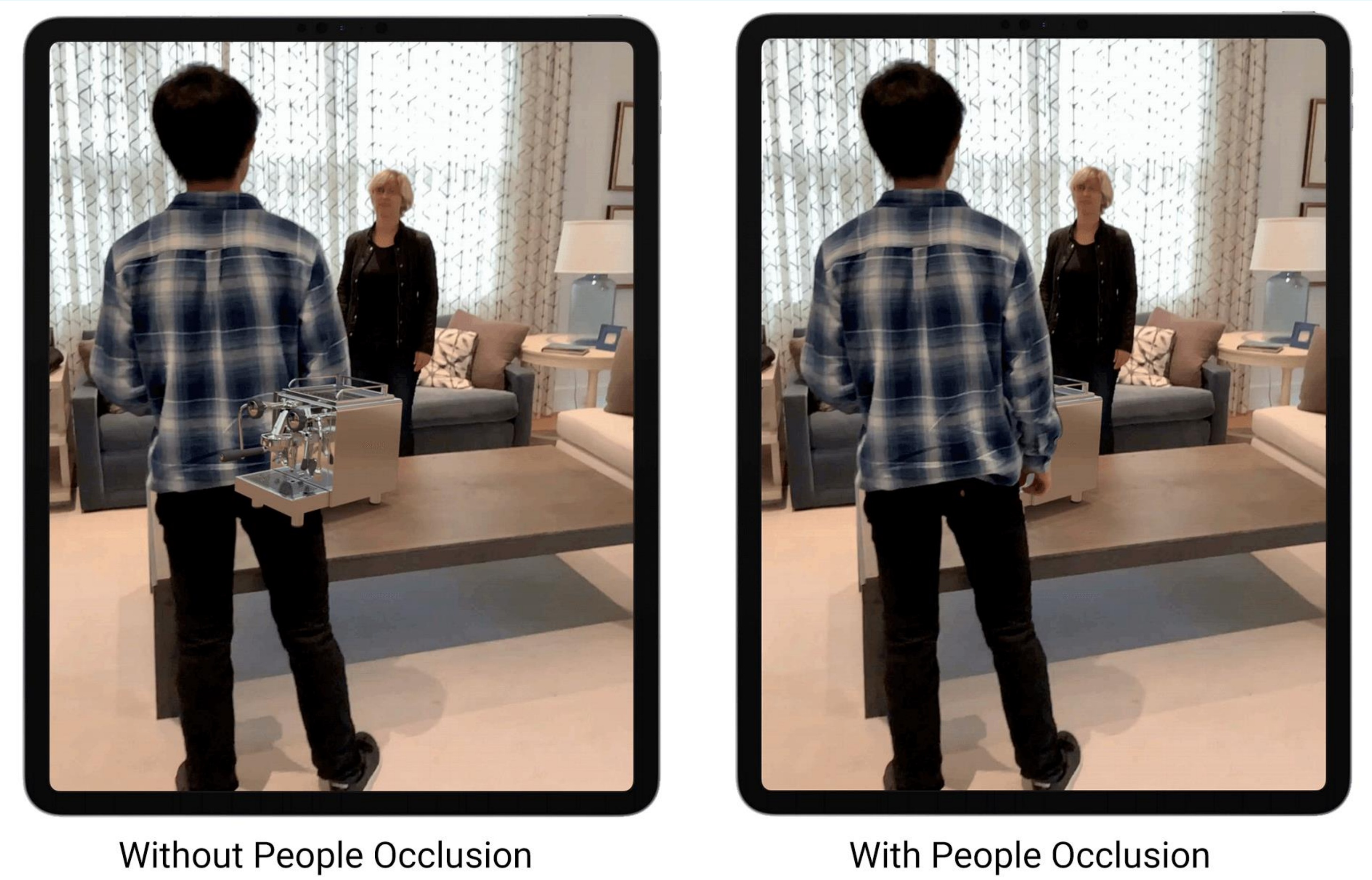
Recent Features

- Plane anchors
- Geolocation anchors
- Limited object detection

Recent Developments in ARCore

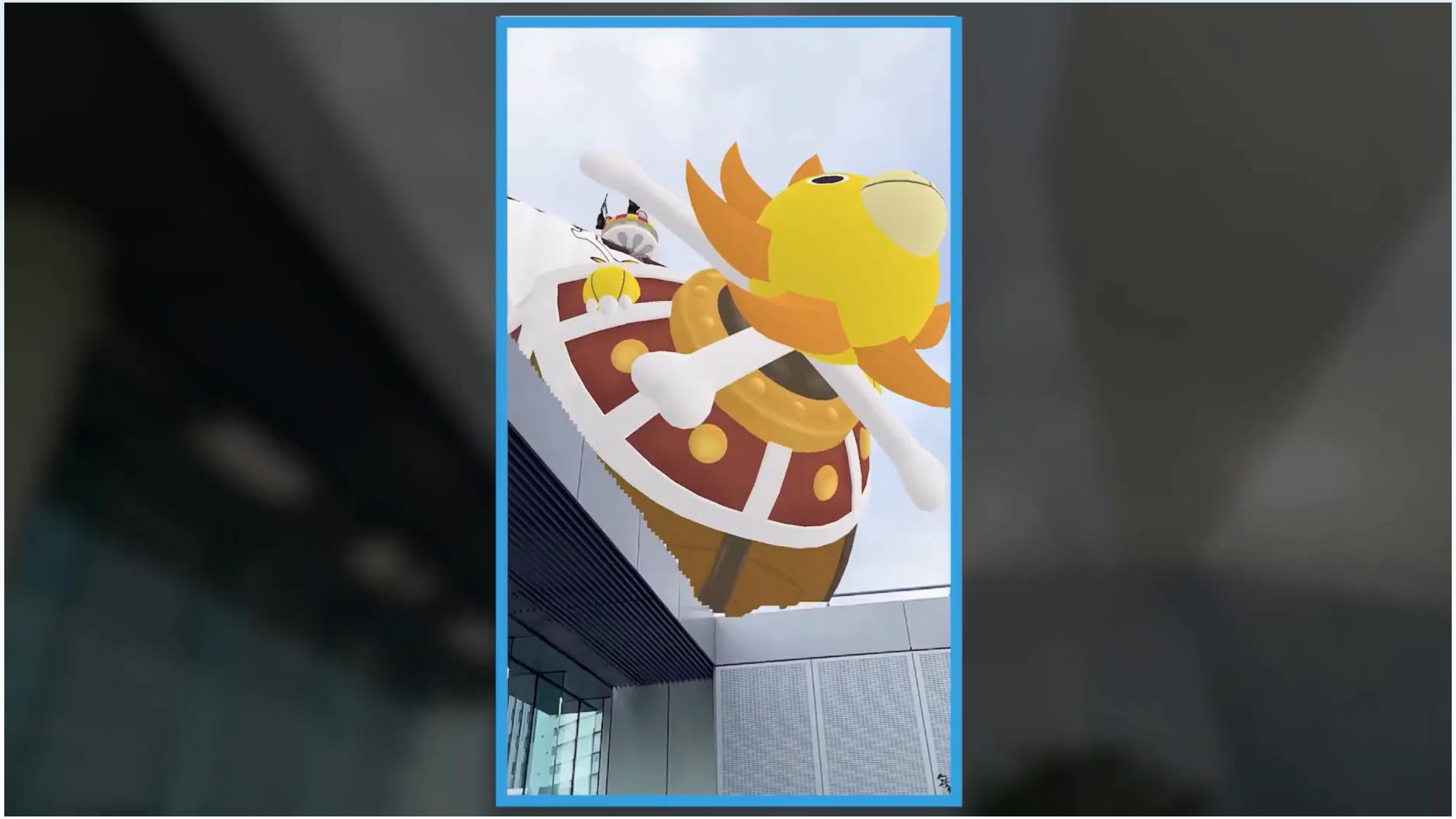
A Deep Dive into ARCore, 2022

Person Detection for Occlusion



From “ARKit 3 brings more power to Apple's Augmented Reality”, 2019

Plane, Sky and Building Detection



[ONE PIECE in augmented reality — NIANTIC LIGHTSHIP ARDK]

Summary

- Tracking is fundamental to VR and AR systems
- There has been a huge development in tracking technologies over the past few years
- Current state-of-the-art systems use hybrid optical / inertial systems
- Mobile phone systems are leading the charge with new levels of scene understanding and tracking