EECE5512
Networked XR Systems

Some slide credits: Anthony Rowe, Intro to XR course, CMU

Last Class - Recap

- Intro to Networked XR Systems
- Hardware aspects
- Software tools

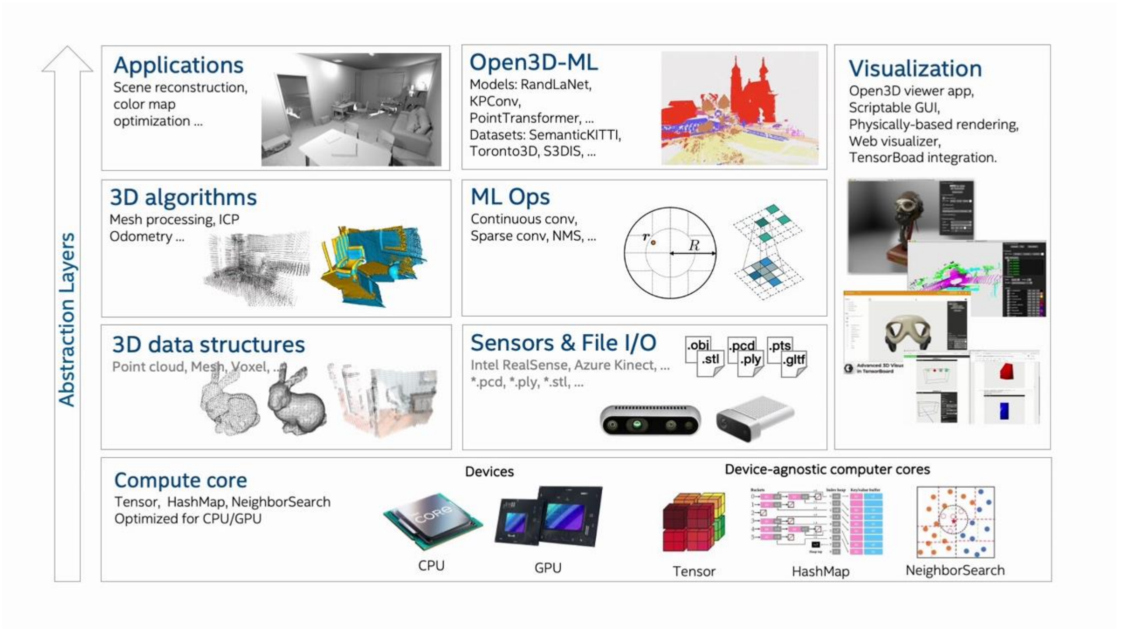
Lecture Outline for Today

- Discuss Homework1
- Software tools
- Internal XR concepts
- Sensors
- Sensing Algorithms

XR SDKs

- Open3D

  Open3D is an open-source library that supports rapid development of software that deals with 3D data. The Open3D frontend exposes a set of carefully selected data structures and algorithms in both C++ and Python. The backend is highly optimized and is set up for parallelization.


Abstraction Layers
Applications
Scene reconstruction, color map optimization ...
Open3D-ML
Models: RandLaNet, KPConv, PointTransformer, ...
Datasets: SemanticKITTI, Toronto3D, S3DIS, ...
Visualization
Open3D viewer app, Scriptable GUI, Physically-based rendering, Web visualizer, TensorBoad integration.
3D algorithms
Mesh processing, ICP
Odometry ...
ML Ops
Continuous conv, Sparse conv, NMS, ...
3D data structures
Point cloud, Mesh, Voxel, ...
Sensors & File I/O
Intel RealSense, Azure Kinect, ...
*.pcd, *.ply, *.stl, ...
.obj .stl .pcd .ply .pts .gltf
Compute core
Tensor, HashMap, NeighborSearch
Optimized for CPU/GPU
Devices
CPU
GPU
Device-agnostic computer cores
Tensor
HashMap
NeighborSearch

https://www.open3d.org/docs/release/tutorial/geometry/mesh.html

XR SDKs

- ARKit – Mobile (Apple)
  - ARKit combines device motion tracking, world tracking, scene understanding, and display conveniences to simplify building an AR experience.

```
let session = ARKitSession()
let worldInfo = WorldTrackingProvider()
```

XR SDKs

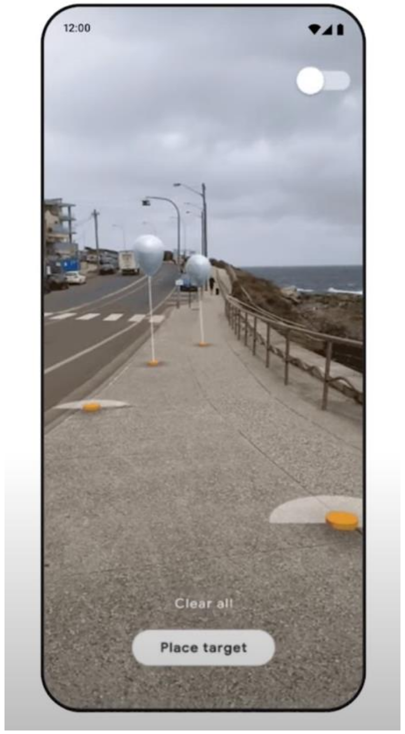
- ARKit – Vision Pro (Apple)
  - Additional features like tracking –Eyes, Hands, Head, etc.

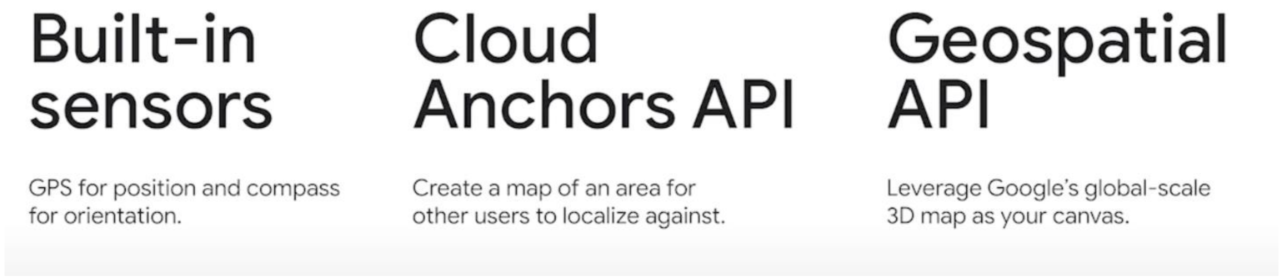
https://developer.apple.com/documentation/arkit/arkit_in_visionos

XR SDKs

- ARCore – Mobile (Android)

  ARCore is Google's augmented reality SDK offering cross-platform APIs to build new immersive experiences on Android, iOS, Unity, and Web.





Built-in sensors

GPS for position and compass for orientation.

Cloud Anchors API

Create a map of an area for other users to localize against.

Geospatial API

Leverage Google's global-scale 3D map as your canvas.

XR SDKs

- Oculus & MRTK

Input System

Hand Tracking (HoloLens 2)

Eye Tracking (HoloLens 2)

Profiles

Hand Tracking (Ultraleap)

UI Controls

Solvers

Multi-Scene Manager

Spatial Awareness

Diagnostic Tool

MRTK Standard Shader Example View

Speech & Dictation

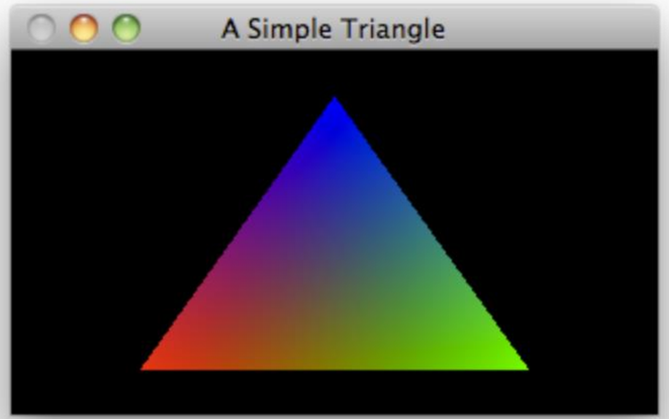
Boundary System

In-Editor Simulation

Experimental Features

XR Native Renderers

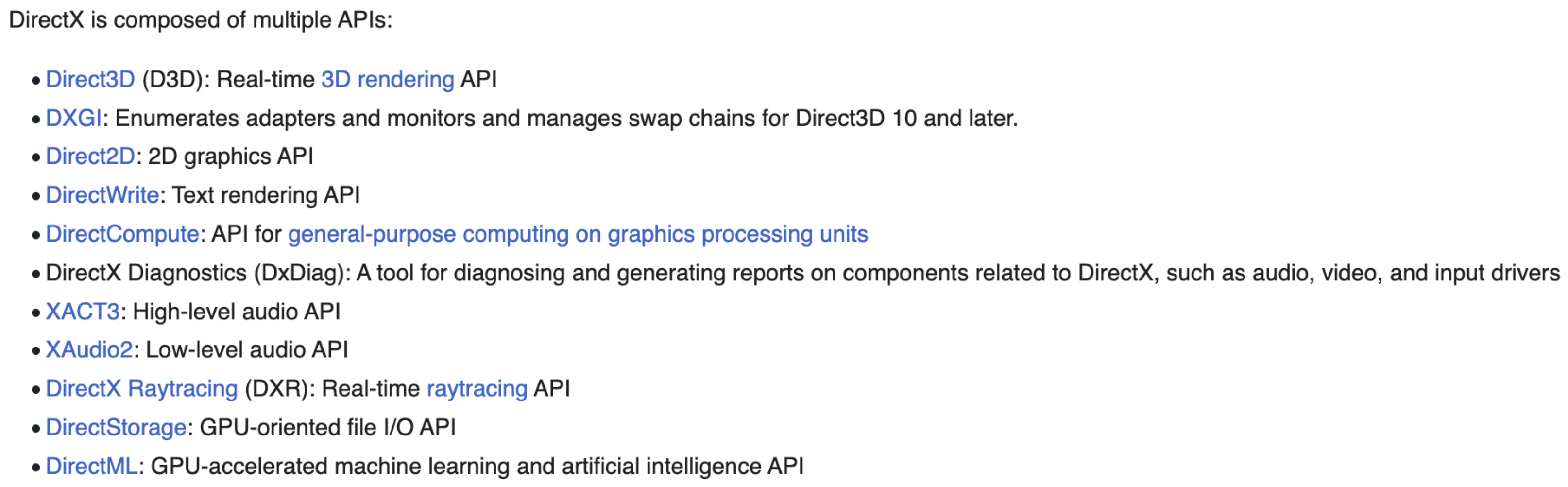
- OpenGL
  - OpenGL is a cross-language, cross-platform application programming interface for rendering 2D and 3D vector graphics. The API is typically used to interact with a GPU, to achieve hardware-accelerated rendering.



https://learnopengl.com/Getting-started/Hello-Triangle

XR Native Renderers

- DirectX
  - Microsoft's graphics API



DirectX is composed of multiple APIs:

- Direct3D (D3D): Real-time 3D rendering API
- DXGI: Enumerates adapters and monitors and manages swap chains for Direct3D 10 and later.
- Direct2D: 2D graphics API
- DirectWrite: Text rendering API
- DirectCompute: API for general-purpose computing on graphics processing units
- DirectX Diagnostics (DxDiag): A tool for diagnosing and generating reports on components related to DirectX, such as audio, video, and input drivers
- XACT3: High-level audio API
- XAudio2: Low-level audio API
- DirectX Raytracing (DXR): Real-time raytracing API
- DirectStorage: GPU-oriented file I/O API
- DirectML: GPU-accelerated machine learning and artificial intelligence API

https://learn.microsoft.com/en-us/windows/win32/directx

XR Native Renderers

- Vulkan
  - Vulkan is a low-level low-overhead, cross-platform API and open standard for 3D graphics and computing. It was originally developed as Mantle by AMD, but was later given to Khronos Group. It was intended to address the shortcomings of OpenGL, and allow developers more control over the GPU.

Vulkan is preferred over OpenGL nowadays

XR 3D Modeling

- Blender
  - Blender is a free and open-source 3D computer graphics software tool set used for creating animated films, visual effects, art, 3D-printed models, motion graphics, interactive 3D applications, virtual reality, and, formerly, video games.

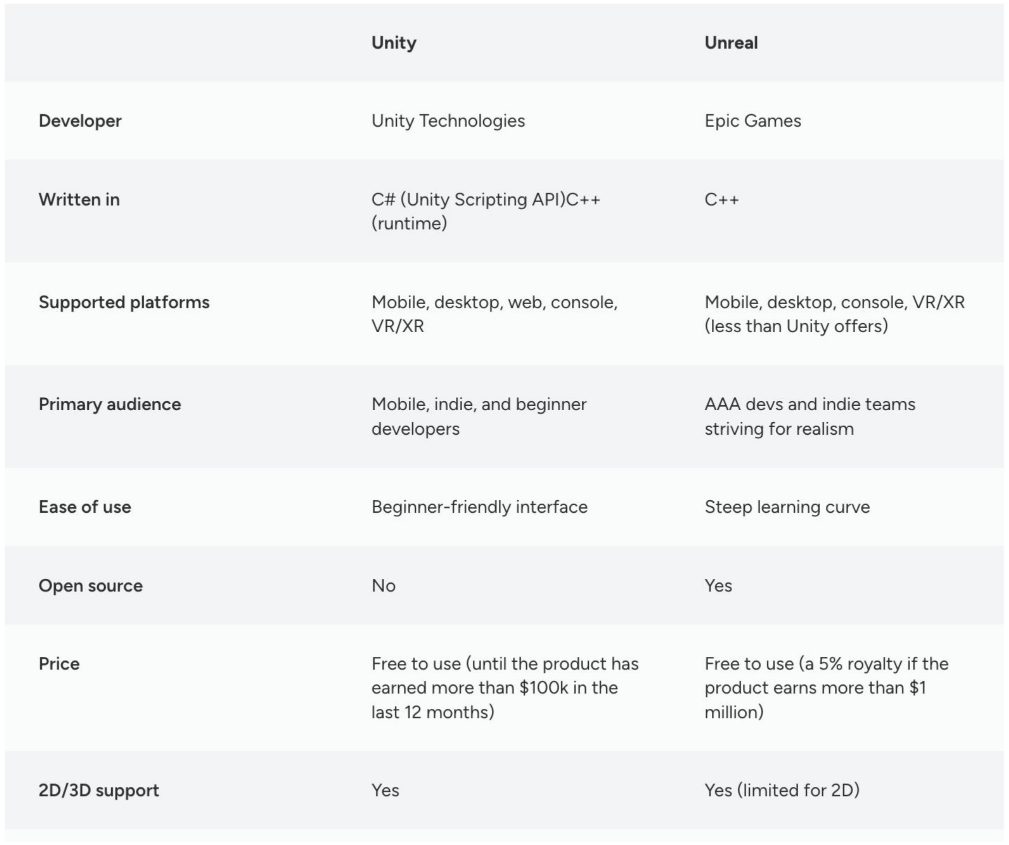
  https://youtu.be/f-mx-Jfx9lA?t=236

XR 3D Modeling

- Maya
  - Better modeling features compared to Blender
  - Mainly for enterprises – not free, not open

XR Gaming Engines

- Unity & Unreal
  - Unity was originally an Apple game engine but slowly spread to many platforms
  - Both provide game developers with a 2D and 3D platform to create video games.



	Unity	Unreal
Developer	Unity Technologies	Epic Games
Written in	C# (Unity Scripting API)C++ (runtime)	C++
Supported platforms	Mobile, desktop, web, console, VR/XR	Mobile, desktop, console, VR/XR (less than Unity offers)
Primary audience	Mobile, indie, and beginner developers	AAA devs and indie teams striving for realism
Ease of use	Beginner-friendly interface	Steep learning curve
Open source	No	Yes
Price	Free to use (until the product has earned more than $100k in the last 12 months)	Free to use (a 5% royalty if the product earns more than $1 million)
2D/3D support	Yes	Yes (limited for 2D)

XR 3D Scanners

- Matterport (https://matterport.com)

https://jamesandharrisoncourt.com/virtual-tours

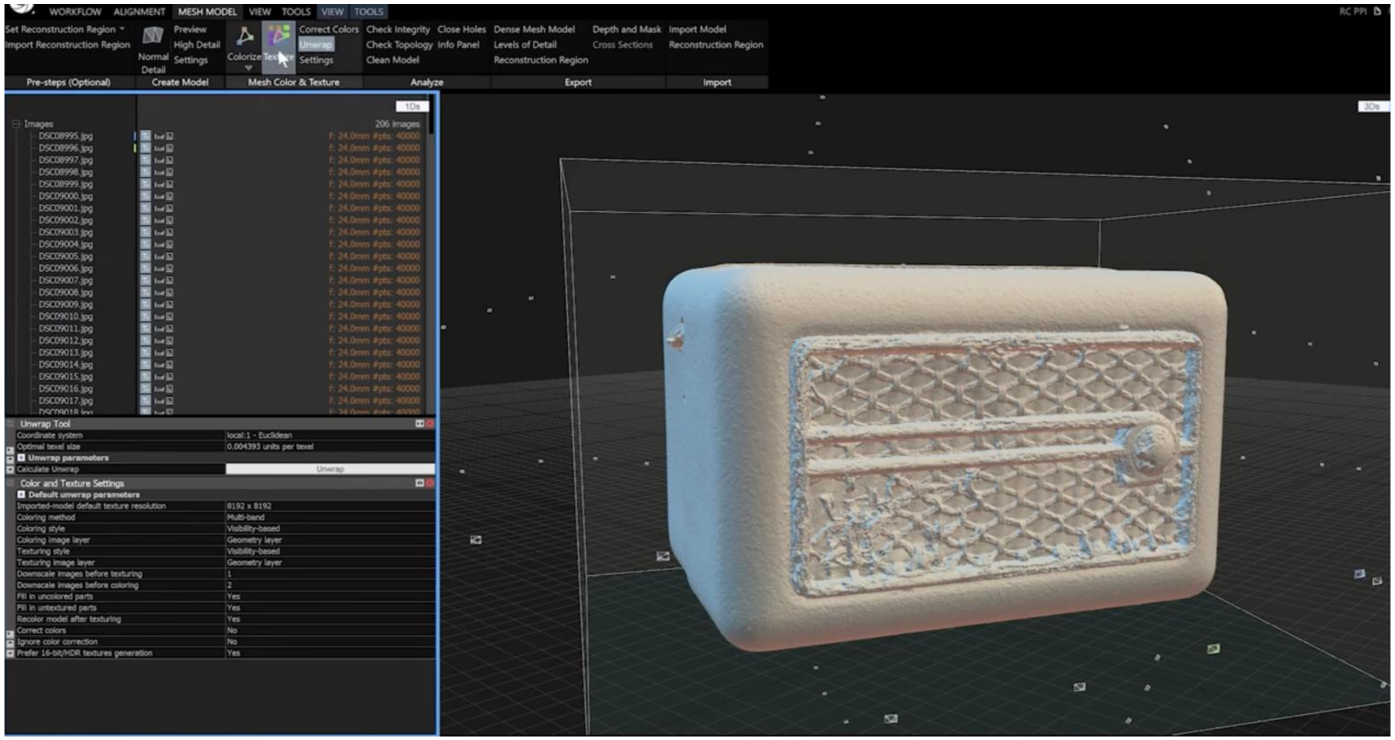
XR 3D Scanners

- Scaniverse (https://scaniverse.com) - Mobile

- a 3D scanning app that supports all recent iPhones and iPads, including those without LiDAR. Scaniverse uses photogrammetry to accurately reconstruct objects, rooms, and even whole buildings and outdoor environments.

XR 3D Scanners

- RealityCapture – photogrammetry + manual editing



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Images                                 206 images
DSC08995.jpg    f: 24.0mm #pts: 40000
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DSC08997.jpg    f: 24.0mm #pts: 40000
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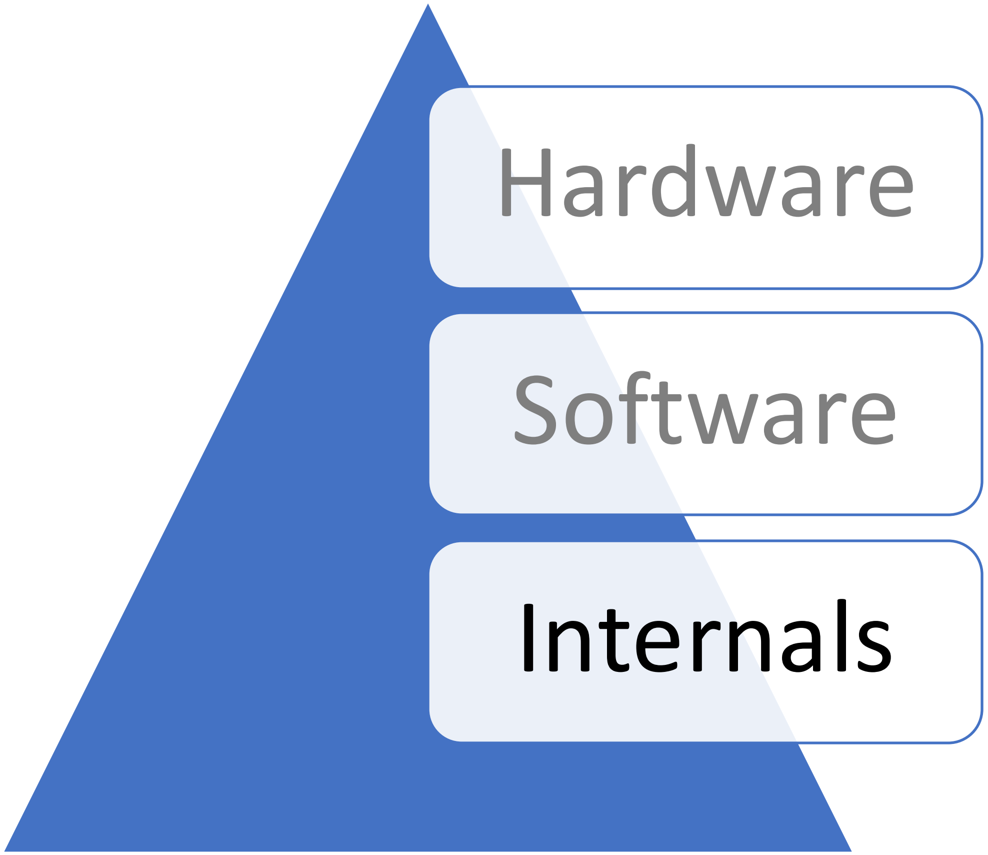
DSC09016.jpg    f: 24.0mm #pts: 40000
DSC09017.jpg    f: 24.0mm #pts: 40000
```

Unwrap Tool	
Coordinate system	local:1 - Euclidean
Optimal texel size	0.004393 units per texel
Unwrap parameters	
Calculate Unwrap	Unwrap

Color and Texture Settings	
Default unwrap parameters	
Imported-model default texture resolution	8192 x 8192
Coloring method	Multi-band
Coloring style	Visibility-based
Coloring image layer	Geometry layer
Texturing style	Visibility-based
Texturing image layer	Geometry layer
Downscale images before texturing	1
Downscale images before coloring	2
Fill in uncolored parts	Yes
Fill in untextured parts	Yes
Recolor model after texturing	Yes
Correct colors	No
Ignore color correction	No
Prefer 16-bit/HDR textures generation	Yes

Lecture Outline for Today

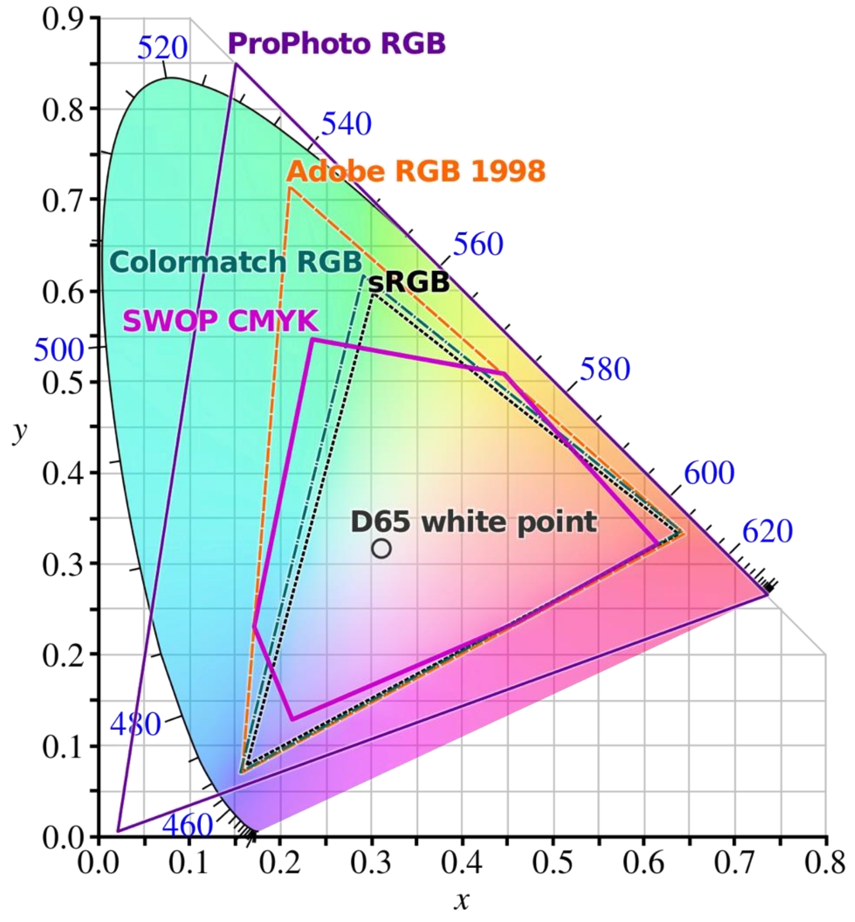


XR Internals

- Perception
- Motion to Photon Latency
- Positioning and Tracking
- 3D Reconstruction
- Real-time Rendering

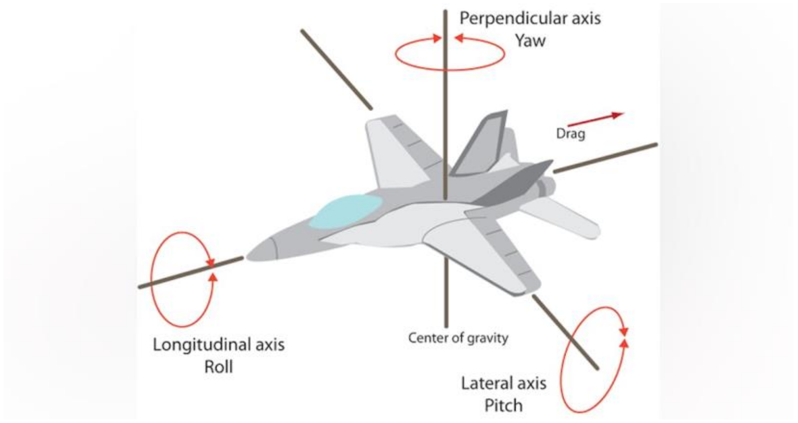
XR Perception

- Visual
  - Color
  - Quality/spatial resolution
  - Depth resolution
  - Temporal resolution
  - Field of view
- Non-visual
  - Sense of touch
  - Audio
  - Balance
  - Smell

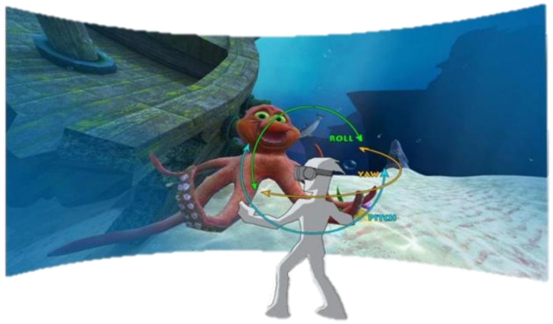


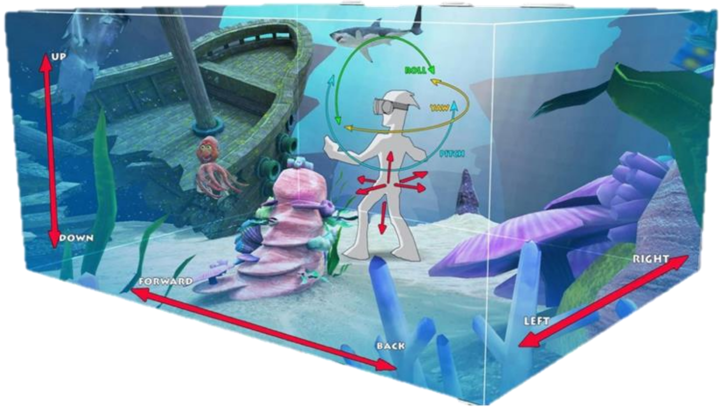
Positioning and Tracking

- You need to know where you are in the world
  - GPS?
  - Visual
  - Inertial
  - Lidar
  - RF



- 3-DoF
- 6-DoF

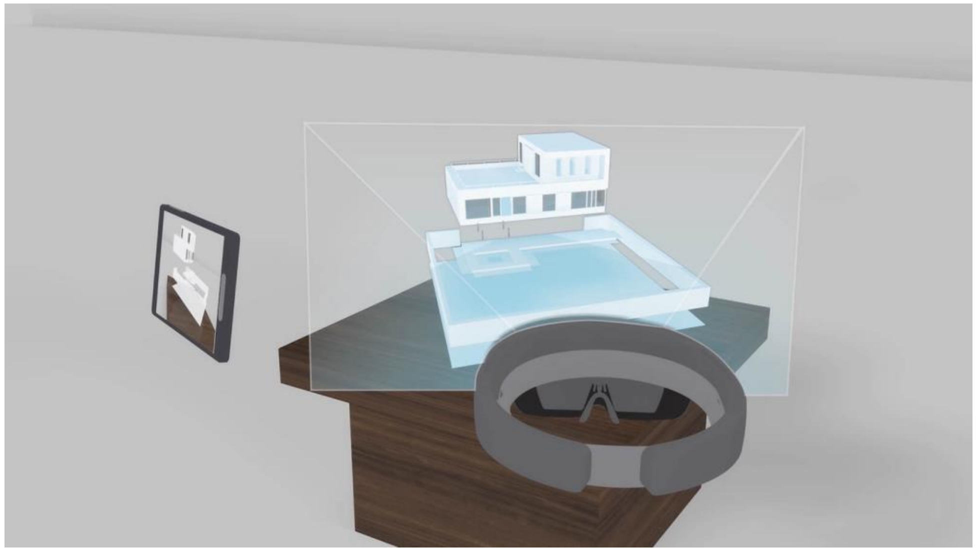




X, Y, Z & Yaw, Pitch, Roll

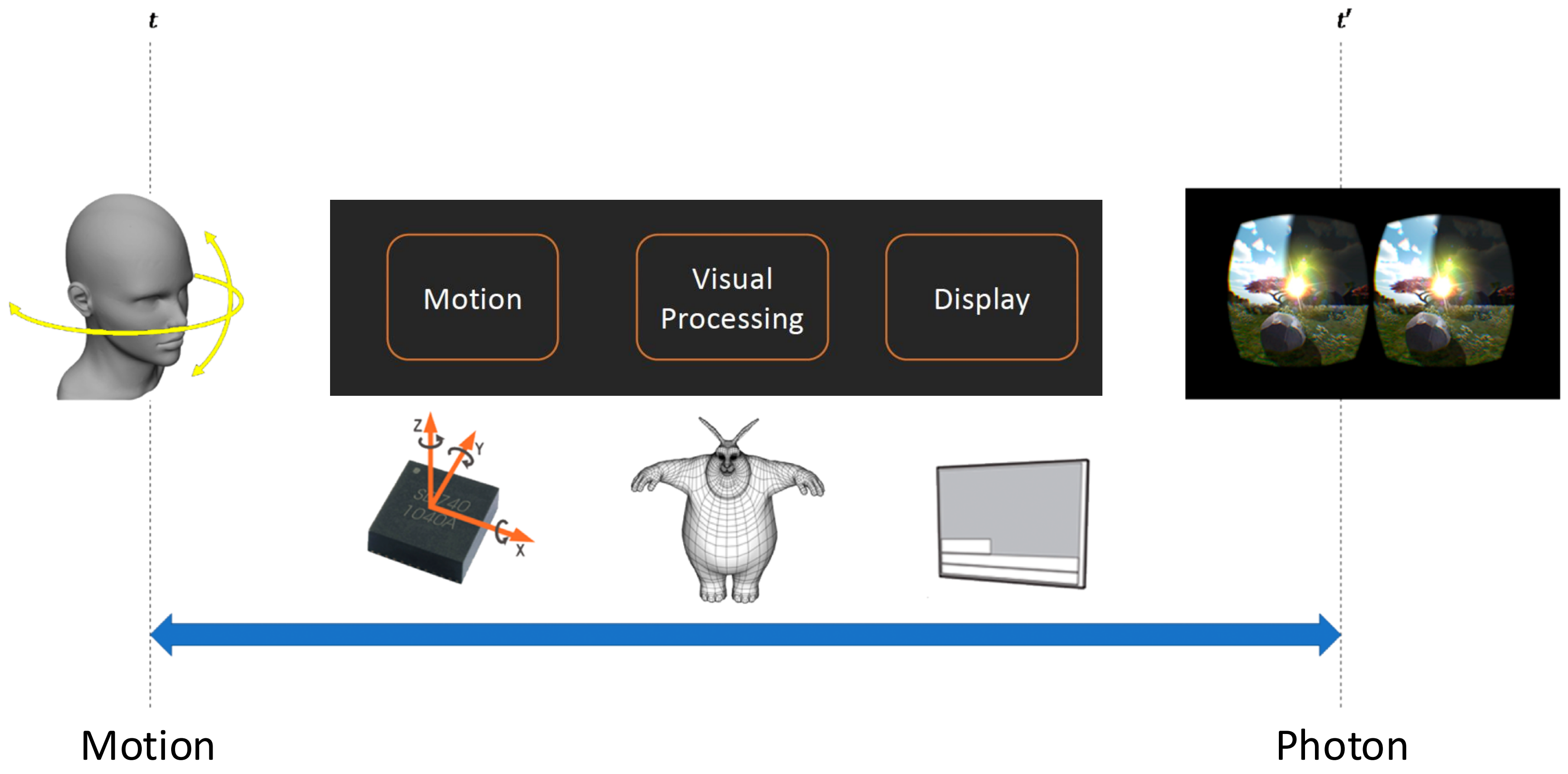
Positioning and Tracking

- Anchors
  - Anchors ensure that objects appear to stay at the same position and orientation in space, helping you maintain the illusion of virtual objects placed in the real world.



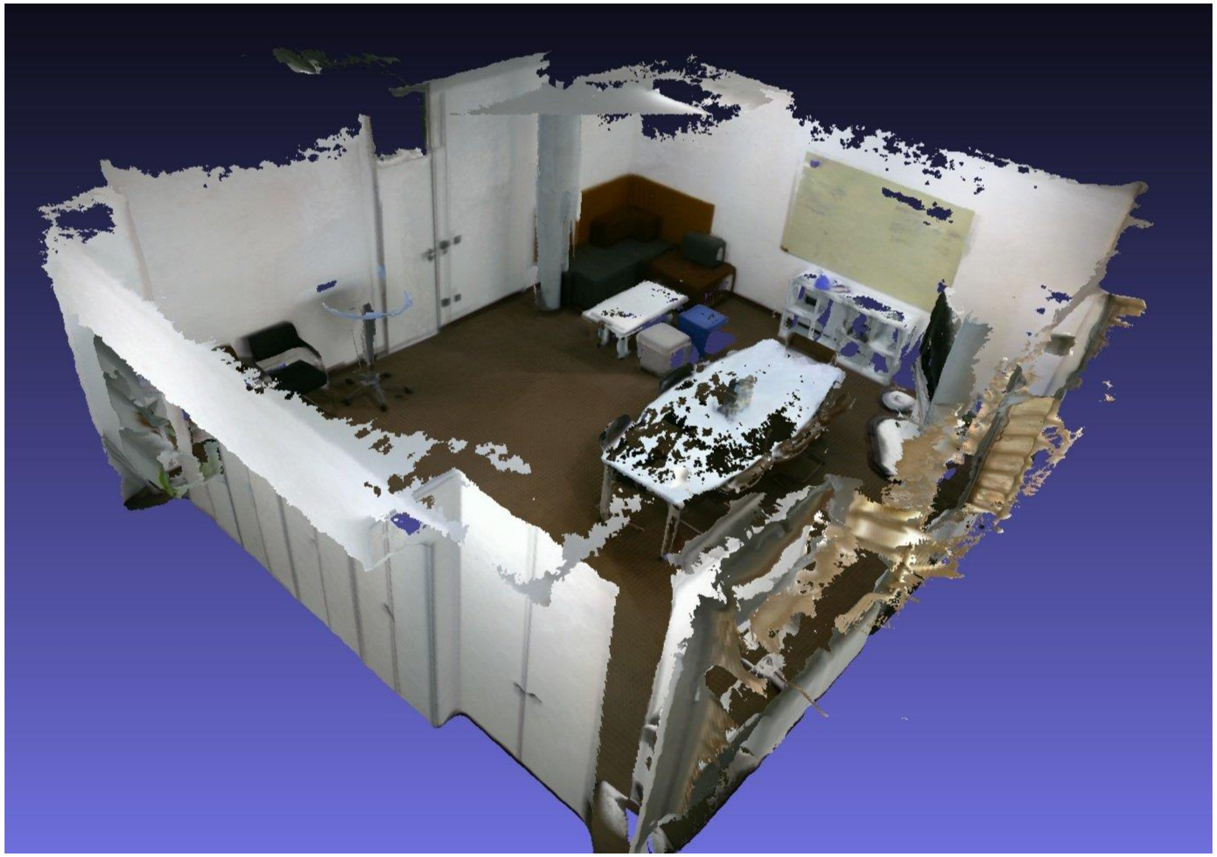
  - Plane
  - Wall
  - Floor
  - Face…
  - Anything that you can identify well

Motion to Photon Latency

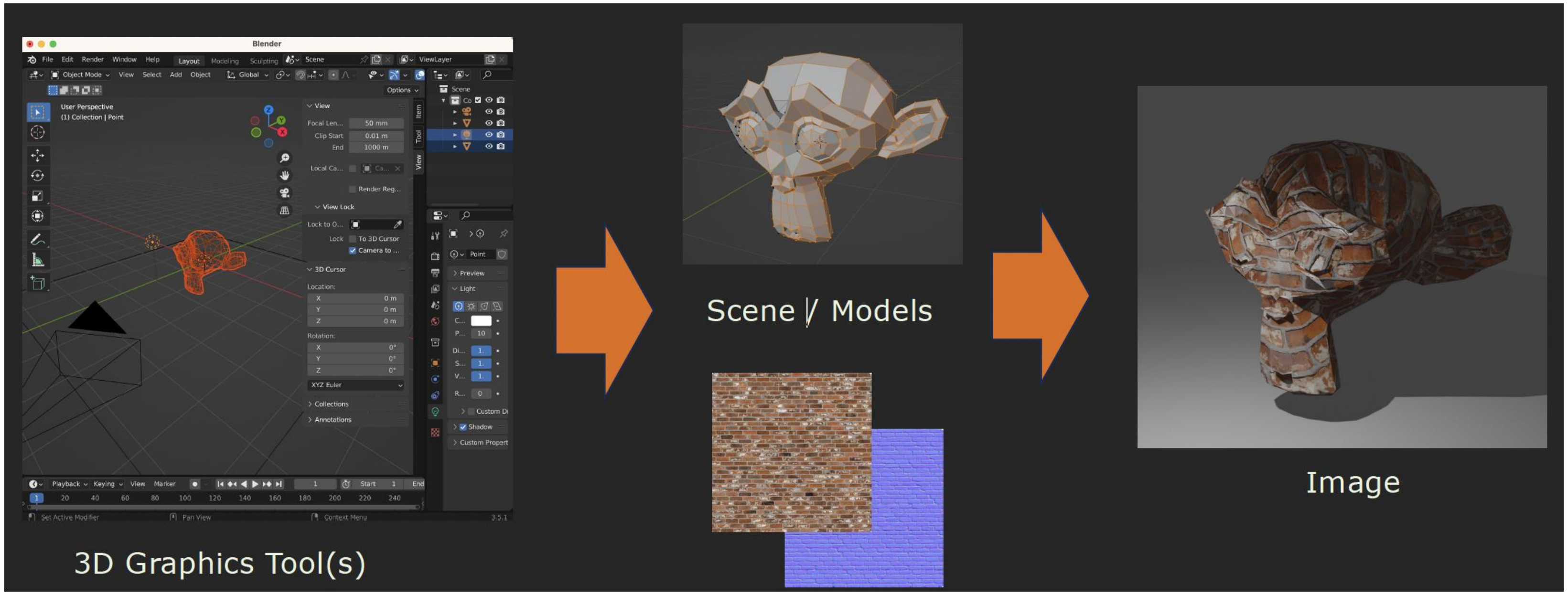


3D Reconstruction

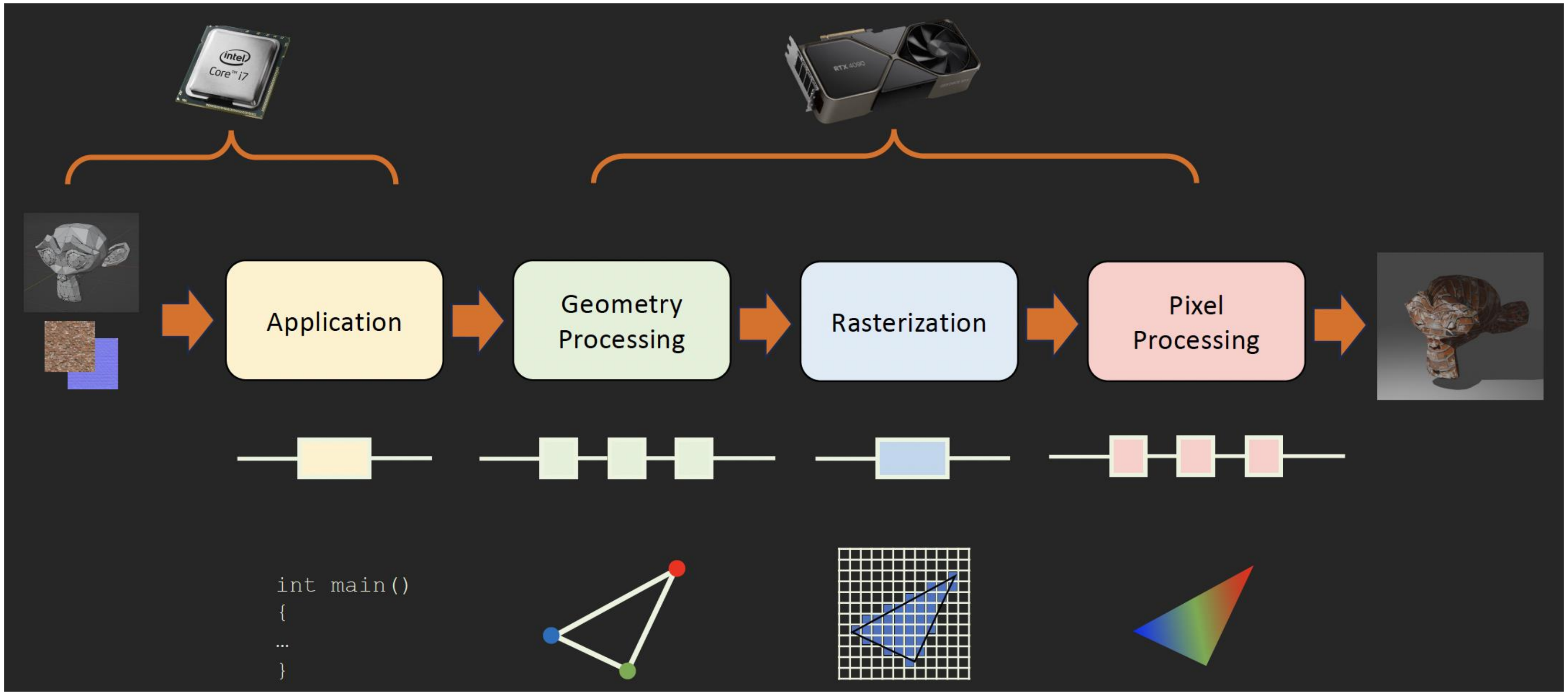
Stitching multiple 2D images to form a 3D image



Real-time Rendering



Real-time Rendering



Lecture Outline for Today

- Software tools
- Internal XR concepts
- Discuss Homework1
- Sensors
- Sensing Algorithms

Sensors and Sensing Algorithms

- Popular Sensors
  - Color camera
  - Depth camera
  - Microphone
  - Inertial
  - Gyro
  - RF
- E.g., Functionality
  - Positioning
  - Tracking
  - 3D Scene Reconstruction

Positioning and Tracking

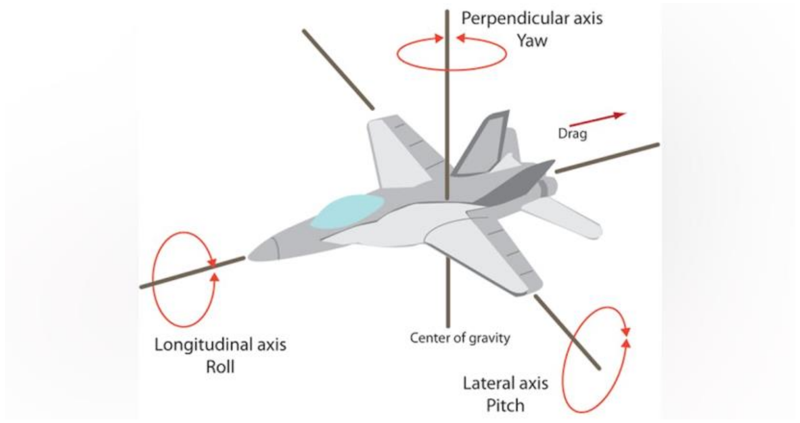
- What to position and track?
  - Users
    - Hands
    - Face
    - Eyes
    - Head
    - Body
    - Activity
    - Physiological signals
  - Environment
    - Objects

Positioning and Tracking

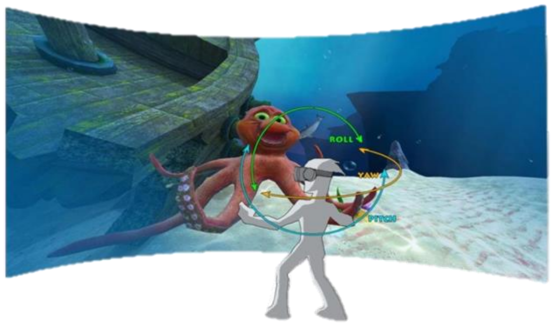
- Why do we need it?
  - For view port control
  - Place virtual content
  - Interact with virtual content
  - Occlusion
  - Adaptive rendering
  - Persistent anchors
  - And more…

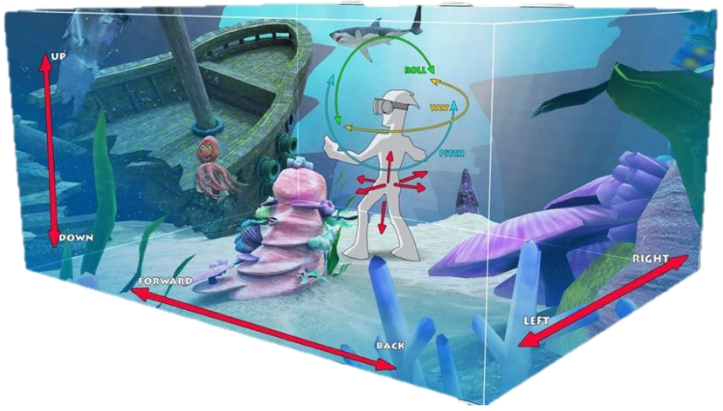
Positioning and Tracking

- You need to know where you are in the world
    - GPS?
    - Visual
    - Inertial
    - Lidar
    - RF



- 3-DoF
- 6-DoF





X, Y, Z & Yaw, Pitch, Roll

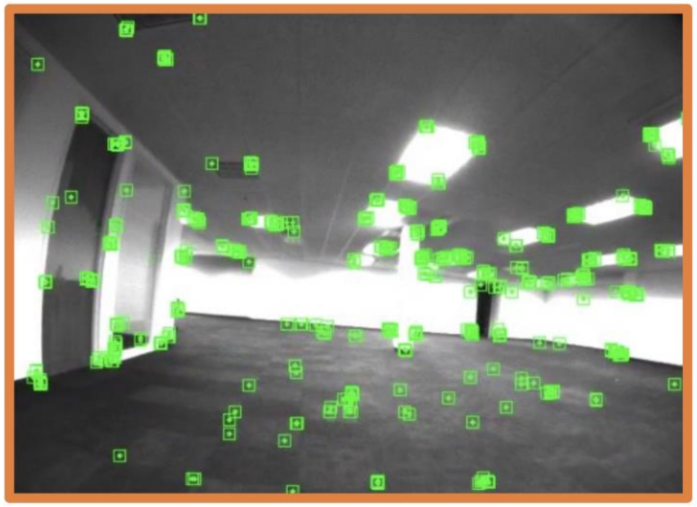
Positioning and Tracking

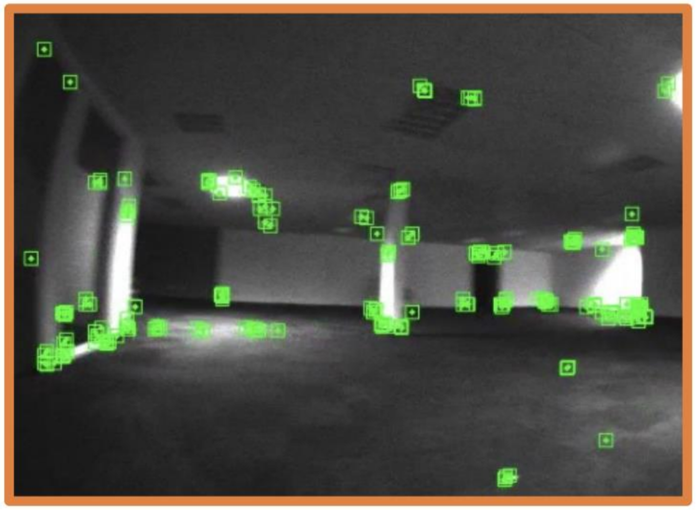
- Typical metrics of importance
  - Accuracy
  - Latency
  - Tracking drift
  - Tracking jitter
  - Update rate
  - Reliability

Visual Tracking Algorithm

- Step1: Capture images
  - Mono or Stereo or multiple cameras
- Step2: Feature Extraction
  - Features are detected in the first frame, and then matched in the second frame.

ORB, SIFT, FAST, BRIEF, etc.


(a) Well-lit (568 matches)


(b) Dim-lit (252 matches)

Visual Tracking Algorithm

- Step1: Capture images
  - Mono or Stereo or multiple cameras
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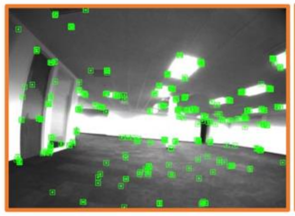
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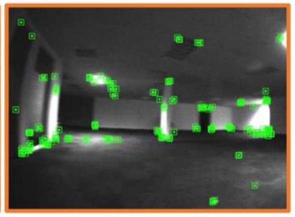
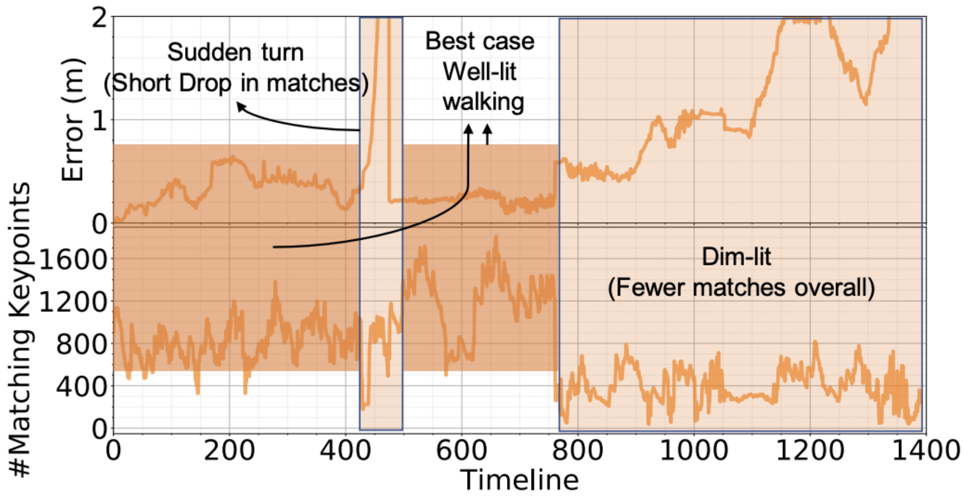
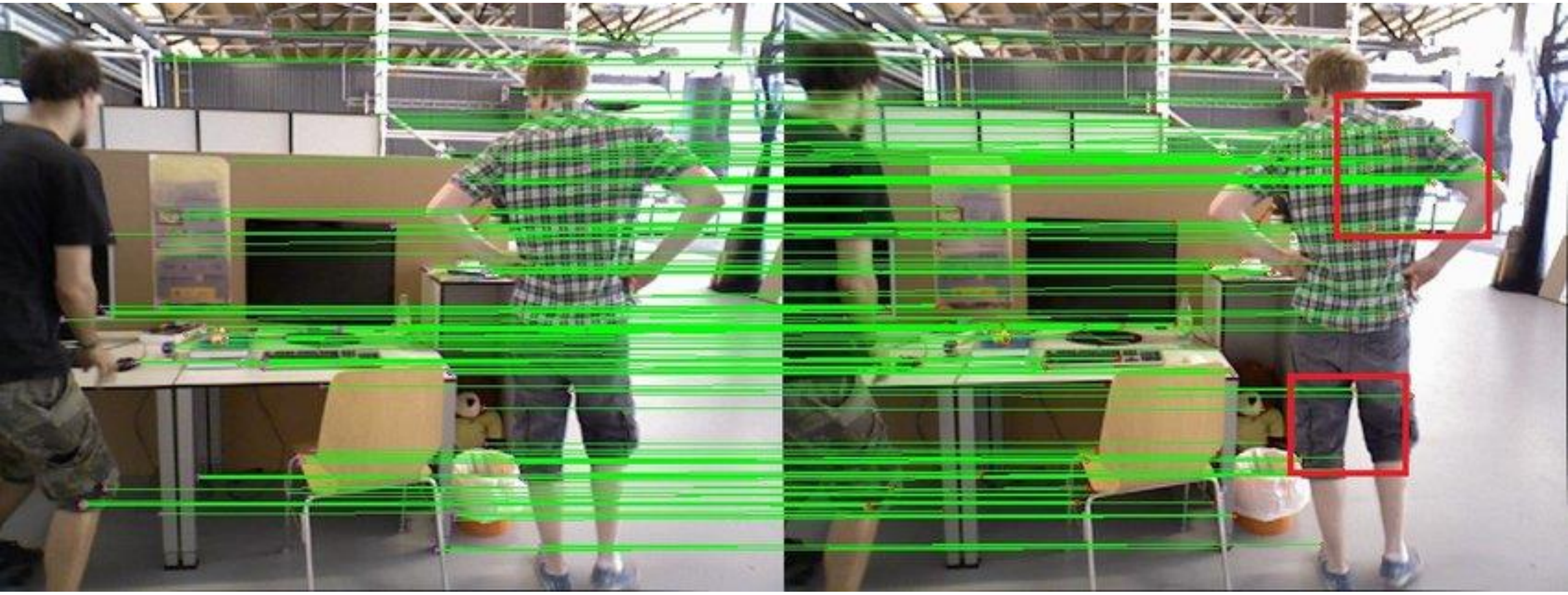

(b) Dim-lit (252 matches)



(c) Matches vs. Error

Visual Tracking Algorithm

- Step3: Optical flow estimation



Get rid of outliers

Visual Tracking Algorithm

- Step4: Estimate camera motion from optical flow

  The optical flow field illustrates how features diverge from a single point, the *focus of expansion*. The focus of expansion can be detected from the optical flow field, indicating the direction of the motion of the camera, and thus providing an estimate of the camera motion.

Commonly used visual tracking tools

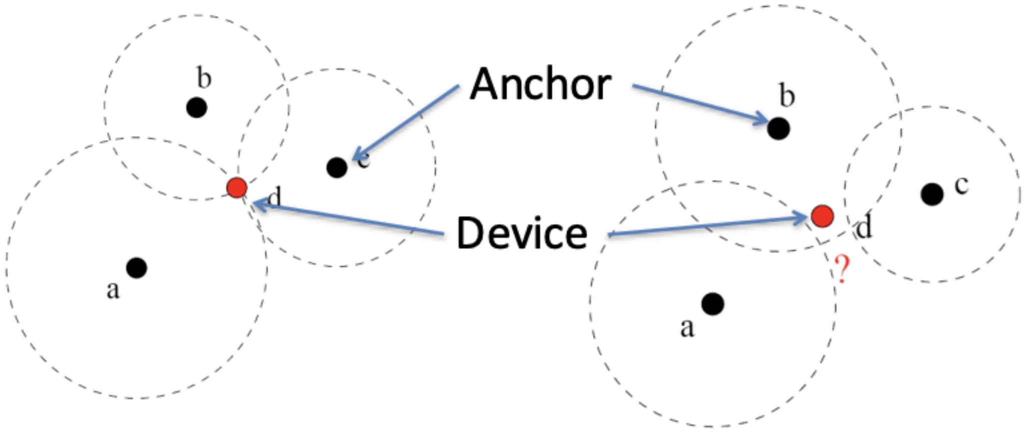
- ARKit, ARCore
- ORBSLAM series
- PTAM
- OpenVSLAM
- Kimera

Visual Tracking Algorithm

- Limitations:
  - Heavily depends on the environment
    - Lighting conditions
    - Geometry of the objects in the environment
    - Uniform surfaces or color
    - Moving objects
    - Fails when too close to objects; camera view occluded

RF-based Tracking

- Range based tracking
  - Convert received signal strength (RSS) or signal timing to a distance estimate with respect to anchor nodes with known locations.
  - Problem: distance estimates may be erroneous, and the circles may not intersect at a single point.



RF-based Tracking

How to estimate location when the circles do not intersect?

Idea: localize at a point that presents the minimum error to the circles by some reasonable error measure.

k anchors at positions (x_i, y_i)

Assume node to be localized has actual location at (x_0, y_0)

Distance estimate between node 0 and anchor *i* is r_i

Error:

$$f_i = r_i - \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2}$$

RF-based Tracking

Linearization and Min Mean Square Estimate

- Ideally, we would like the error to be 0

$$f_i = r_i - \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2} = 0$$

- Re-arrange:

$$(x_0{}^2 + y_0{}^2) + x_0(-2x_i) + y_0(-2y_i) - r_i^2 = -x_i^2 - y_i^2$$

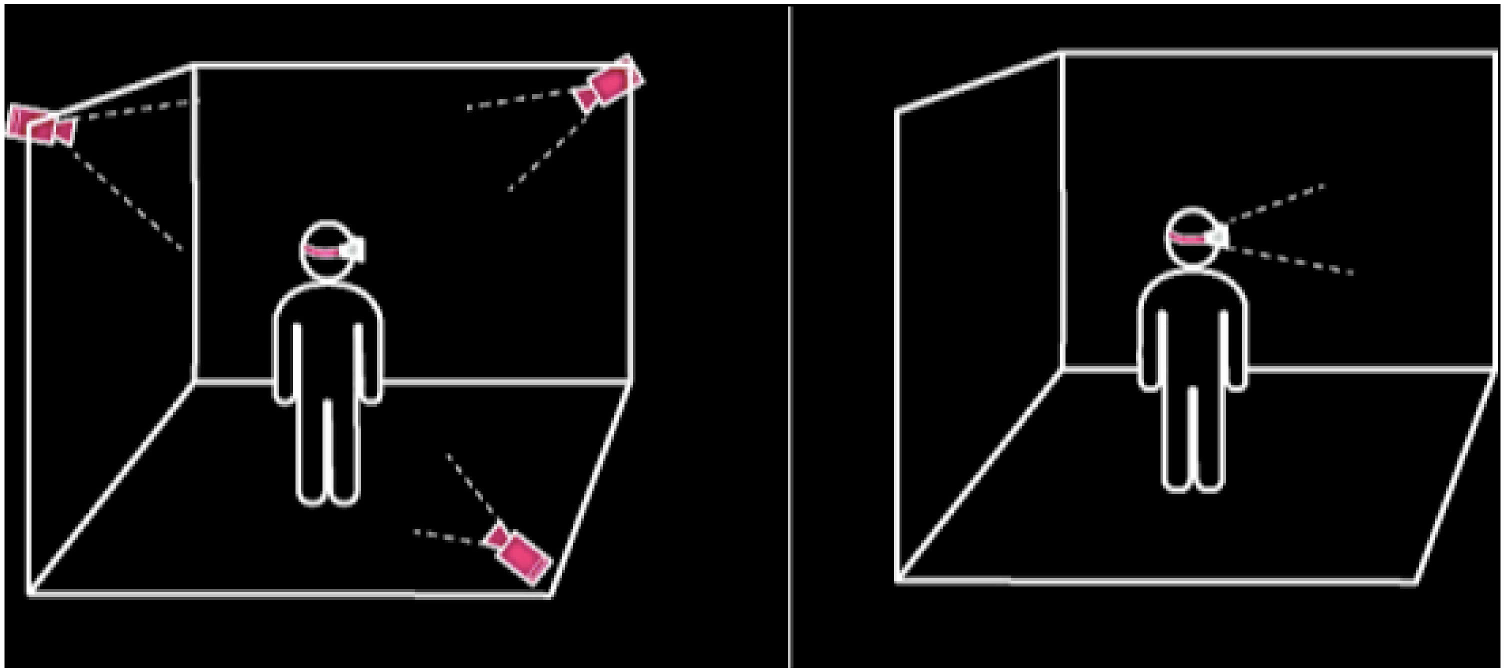
- Subtract the last equation from the previous ones to get rid of quadratic terms.

$$2x_0(x_k - x_i) + 2y_0(y_k - y_i) = r_i^2 - r_k{}^2 - x_i^2 - y_i^2 + x_k^2 + y_k^2$$

- Note that this is linear.

https://en.wikipedia.org/wiki/Ordinary_least_squares

Outside in and Inside out Tracking



Outside in

Inside out

Inertial sensing

- Accelerometer & Gyroscope
  - Measuring linear acceleration (accelerometer) and / or angular orientation rates (gyroscope)
  - No transmitter, cheap, small, high frequency, wireless

https://youtu.be/-0hSQFbt67U?t=24

Inertial sensing

1. Acceleration Measurement

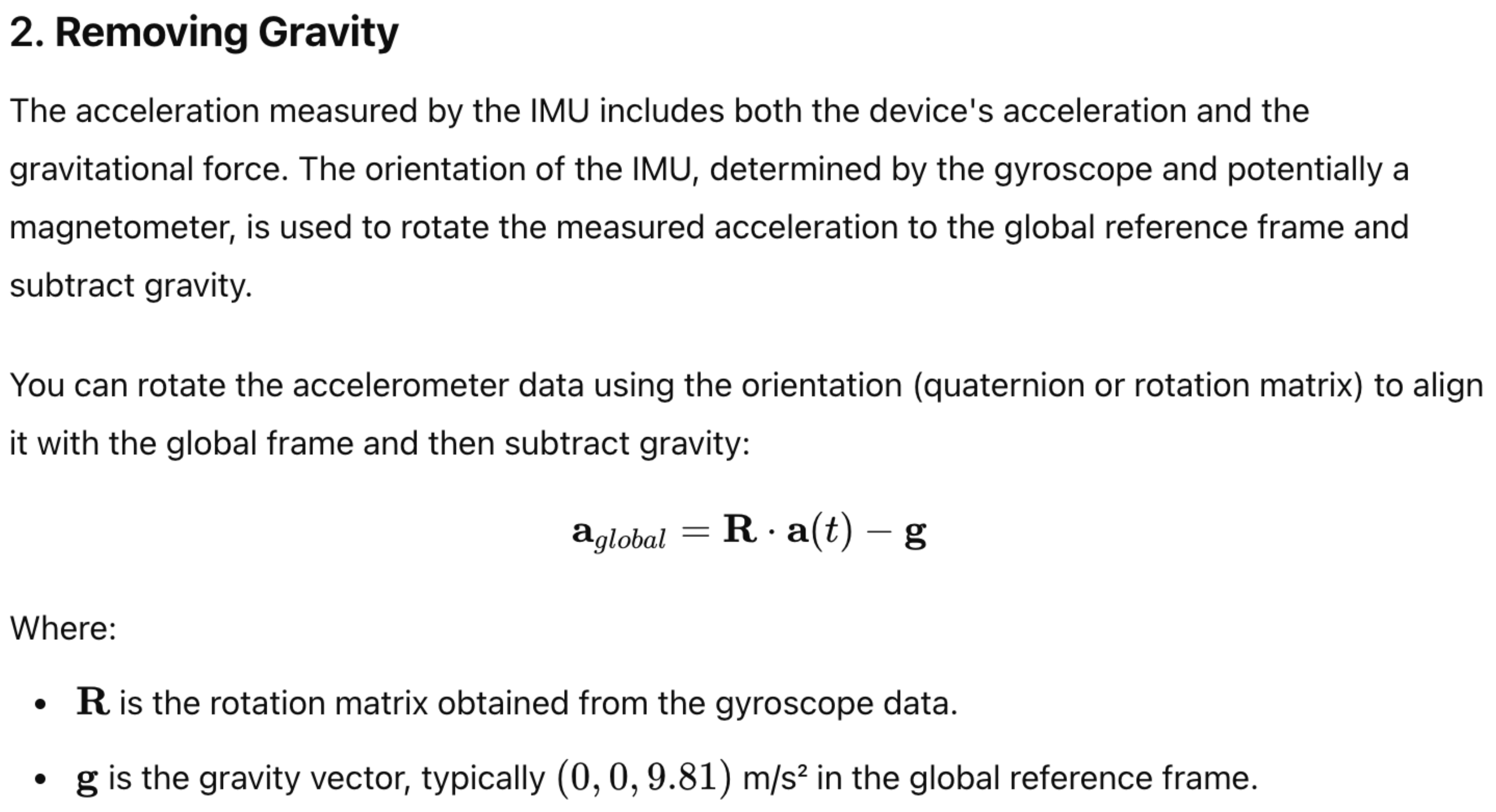
The IMU's accelerometer measures linear acceleration in three axes (a_x, a_y, a_z) relative to its local frame of reference. This is the starting point for position tracking.

Equation for acceleration:

$$\mathbf{a}(t) = \begin{pmatrix} a_x(t) \\ a_y(t) \\ a_z(t) \end{pmatrix}$$

However, the accelerometer measures the sum of the actual acceleration and gravitational acceleration ($\mathbf{g}$). So to get the actual acceleration, gravity needs to be removed using orientation data from the IMU’s gyroscope.

Inertial sensing



2. Removing Gravity

The acceleration measured by the IMU includes both the device's acceleration and the gravitational force. The orientation of the IMU, determined by the gyroscope and potentially a magnetometer, is used to rotate the measured acceleration to the global reference frame and subtract gravity.

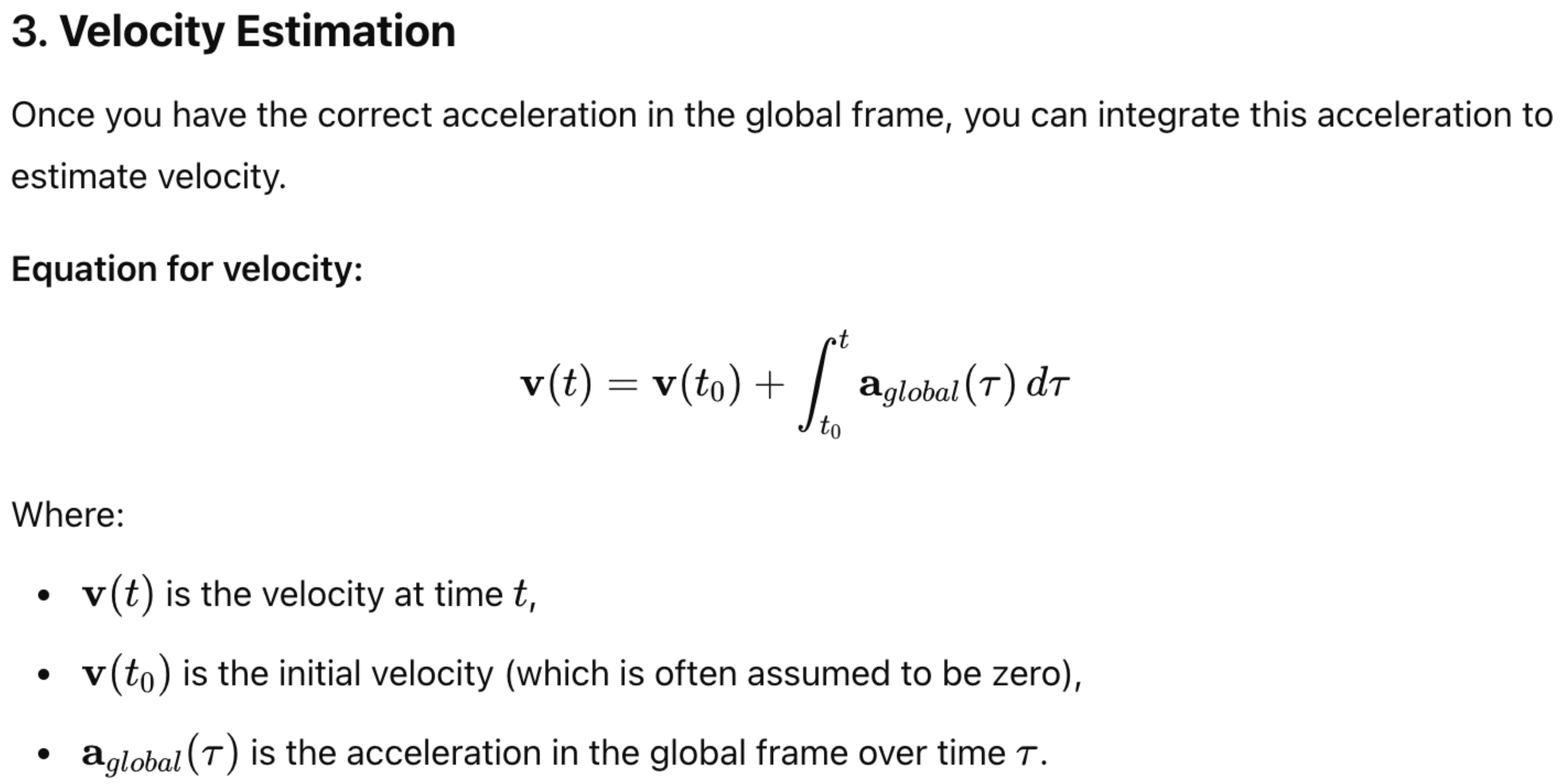
You can rotate the accelerometer data using the orientation (quaternion or rotation matrix) to align it with the global frame and then subtract gravity:

$$\mathbf{a}_{global} = \mathbf{R} \cdot \mathbf{a}(t) - \mathbf{g}$$

Where:

- $\mathbf{R}$ is the rotation matrix obtained from the gyroscope data.
- $\mathbf{g}$ is the gravity vector, typically $(0, 0, 9.81)$ m/s² in the global reference frame.

Inertial sensing



3. Velocity Estimation

Once you have the correct acceleration in the global frame, you can integrate this acceleration to estimate velocity.

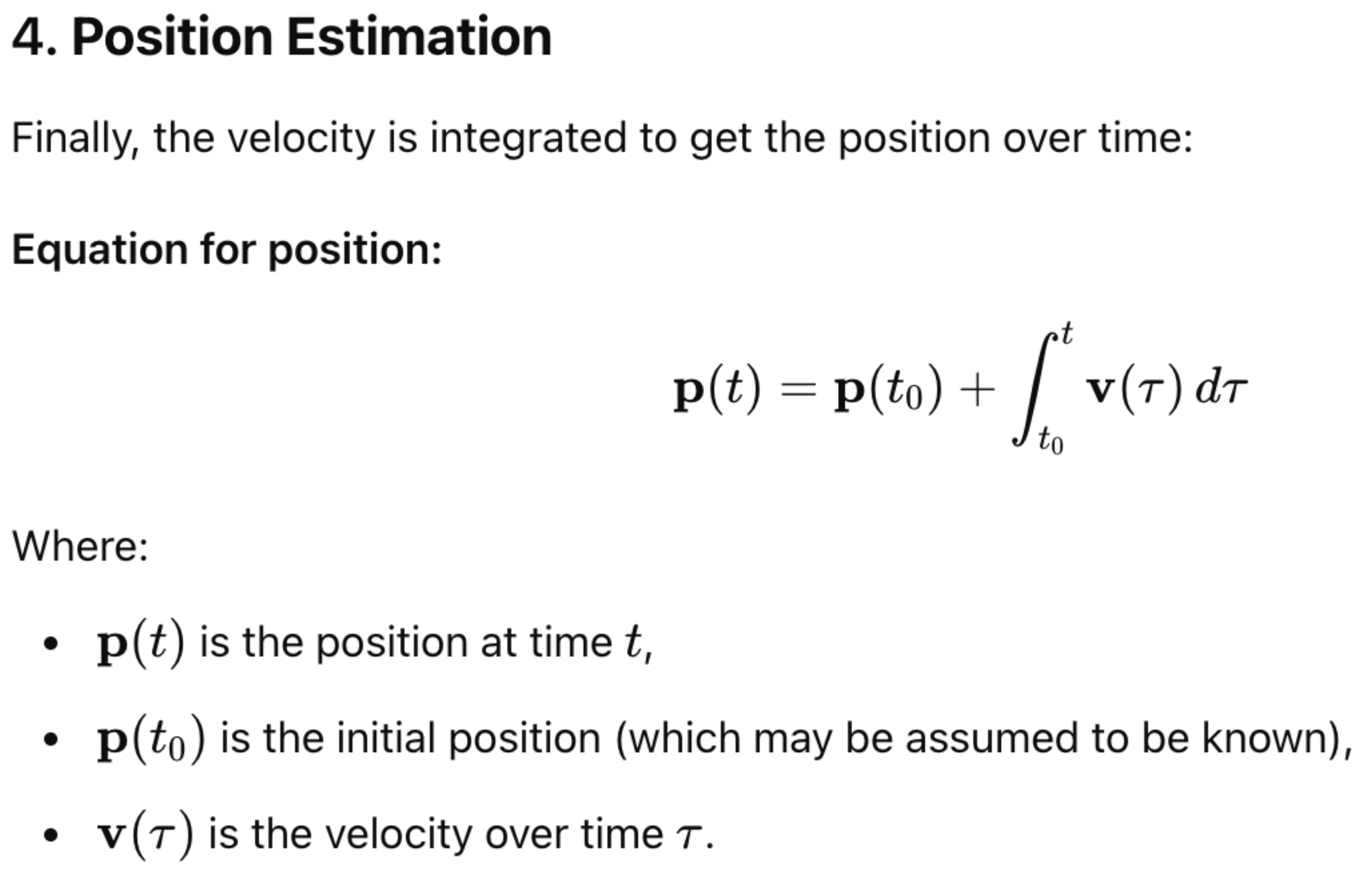
Equation for velocity:

$$\mathbf{v}(t) = \mathbf{v}(t_0) + \int_{t_0}^{t} \mathbf{a}_{global}(\tau)\, d\tau$$

Where:

- $\mathbf{v}(t)$ is the velocity at time t,
- $\mathbf{v}(t_0)$ is the initial velocity (which is often assumed to be zero),
- $\mathbf{a}_{global}(\tau)$ is the acceleration in the global frame over time τ.

Inertial sensing



4. Position Estimation

Finally, the velocity is integrated to get the position over time:

Equation for position:

$$\mathbf{p}(t) = \mathbf{p}(t_0) + \int_{t_0}^{t} \mathbf{v}(\tau)\, d\tau$$

Where:

- $\mathbf{p}(t)$ is the position at time t,
- $\mathbf{p}(t_0)$ is the initial position (which may be assumed to be known),
- $\mathbf{v}(\tau)$ is the velocity over time τ.

IMU Position Tracking Example Problem

An AR/VR headset is equipped with an IMU that provides the following data:

- The headset starts at rest at position $(0, 0, 0)$ and time $t = 0$.
- At $t = 1$ second, the accelerometer readings are $a_x = 2\,\mathrm{m/s}^2$, $a_y = 0\,\mathrm{m/s}^2$, and $a_z = 0\,\mathrm{m/s}^2$.
- The gyroscope indicates that the headset is not rotating (so no need to remove gravity in this case).
- Assume that gravity does not affect the motion since the headset is moving horizontally.

Question:

1. What is the headset's velocity after 1 second?
2. What is the headset's position after 1 second?
3. What happens if the acceleration remains constant for the next 2 seconds (total time = 3 seconds)? Calculate the position at $t = 3$ seconds.

IMU Position Tracking Example Problem

Given:

- Initial velocity $\mathbf{v}(0) = (0, 0, 0)\,\mathrm{m/s}$
- Acceleration $\mathbf{a} = (2, 0, 0)\,\mathrm{m/s}^2$

Velocity is calculated by integrating the acceleration over time:

$$\mathbf{v}(t) = \mathbf{v}(0) + \int_0^1 \mathbf{a}(t)\,dt$$

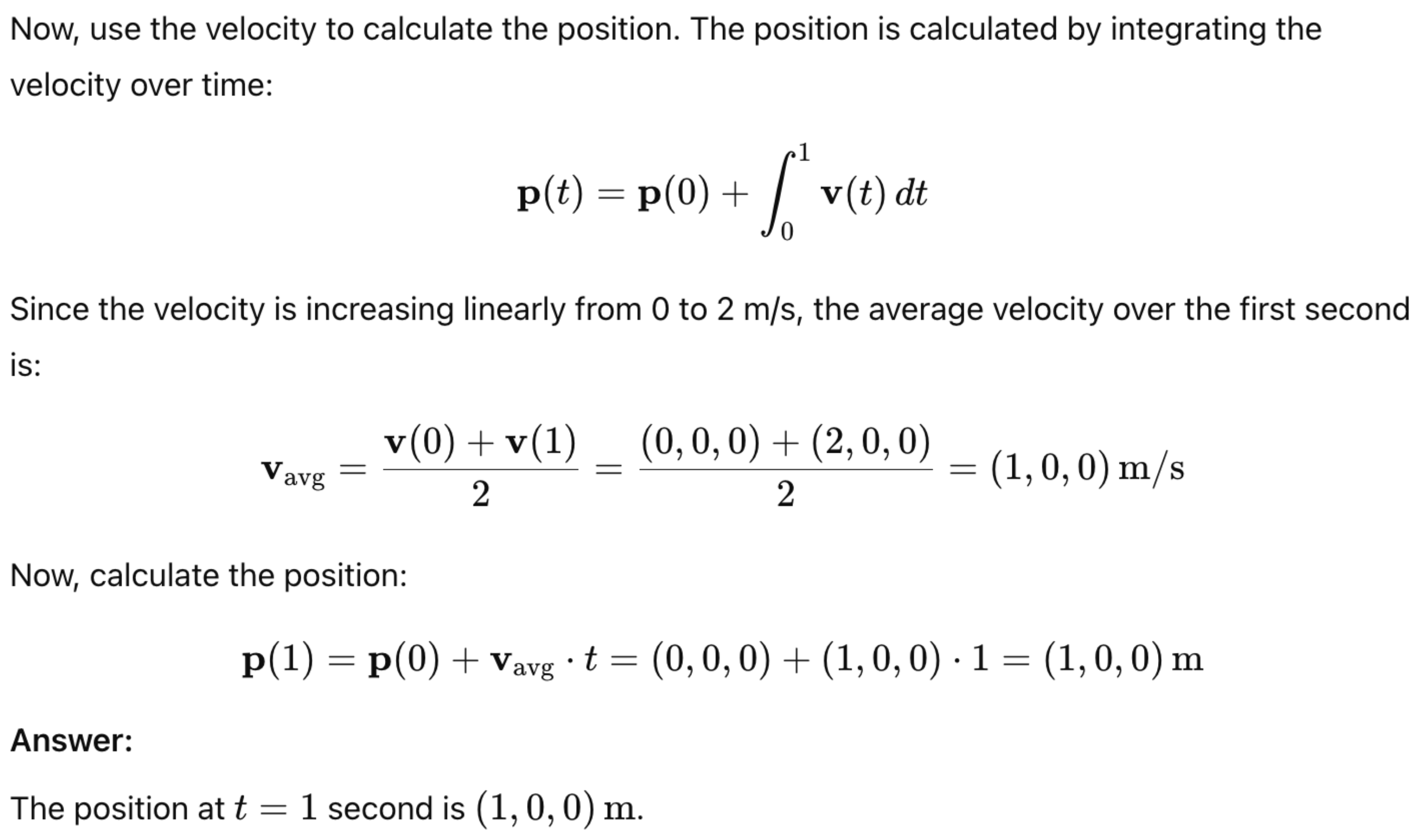
Since the acceleration is constant, the velocity after 1 second is:

$$\mathbf{v}(1) = \mathbf{v}(0) + \mathbf{a} \cdot t = (0, 0, 0) + (2, 0, 0) \cdot 1 = (2, 0, 0)\,\mathrm{m/s}$$

Answer:

The velocity at $t = 1$ second is $(2, 0, 0)\,\mathrm{m/s}$.

IMU Position Tracking Example Problem



Now, use the velocity to calculate the position. The position is calculated by integrating the velocity over time:

$$\mathbf{p}(t) = \mathbf{p}(0) + \int_0^1 \mathbf{v}(t)\,dt$$

Since the velocity is increasing linearly from 0 to 2 m/s, the average velocity over the first second is:

$$\mathbf{v}_{\text{avg}} = \frac{\mathbf{v}(0) + \mathbf{v}(1)}{2} = \frac{(0,0,0) + (2,0,0)}{2} = (1,0,0)\,\text{m/s}$$

Now, calculate the position:

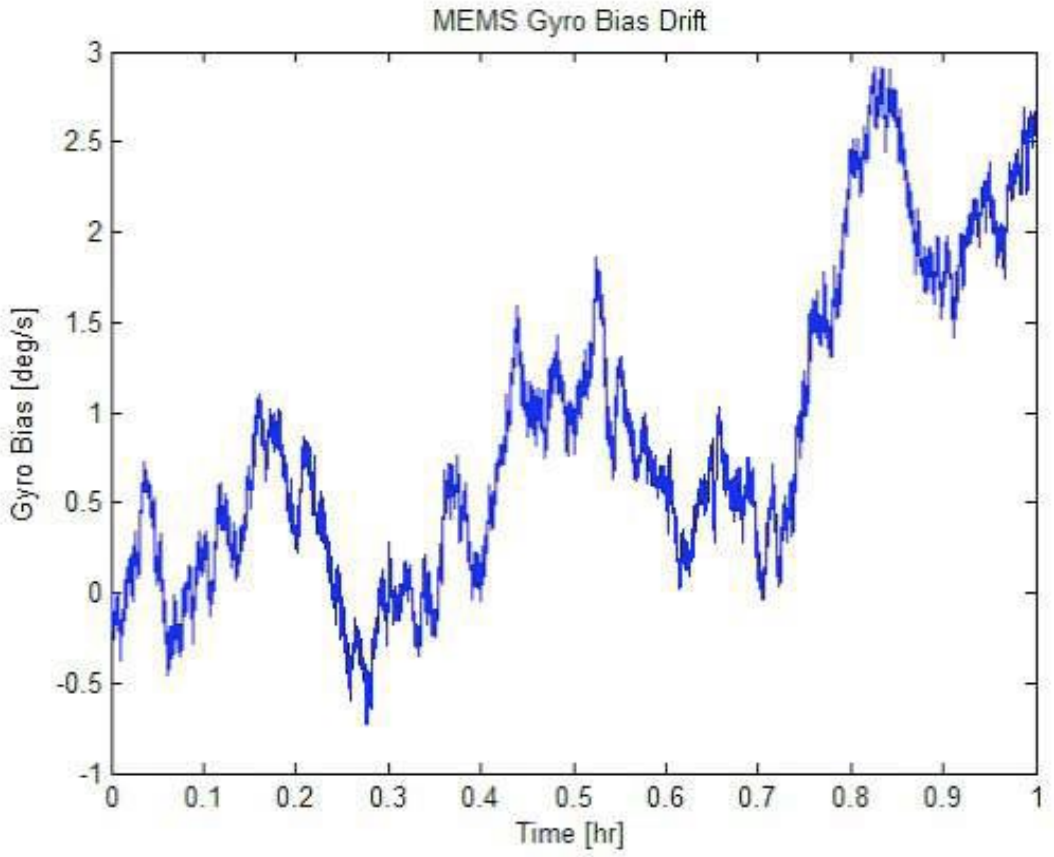
$$\mathbf{p}(1) = \mathbf{p}(0) + \mathbf{v}_{\text{avg}} \cdot t = (0,0,0) + (1,0,0) \cdot 1 = (1,0,0)\,\text{m}$$

Answer:

The position at $t = 1$ second is $(1,0,0)\,\text{m}$.

Inertial sensing

- Drift

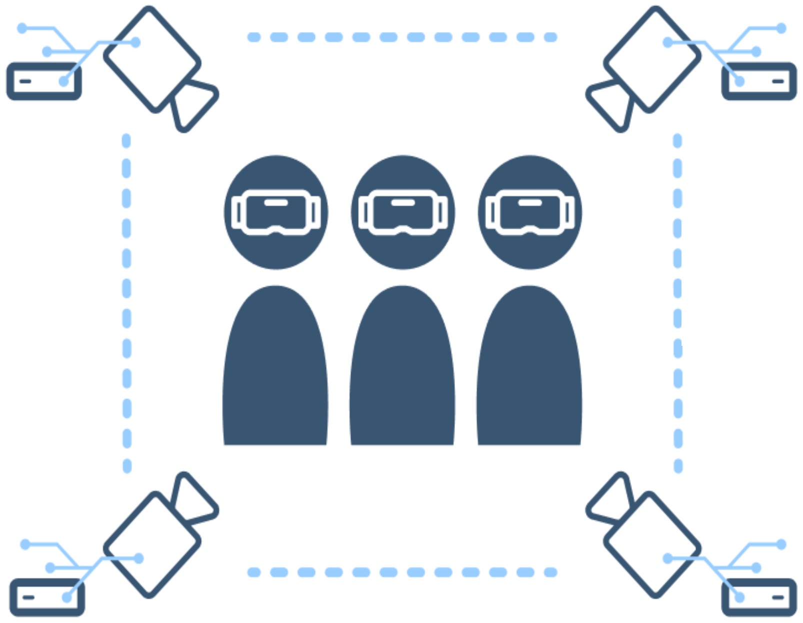


3D Reconstruction Algorithm

- Camera Calibration
- Depth Sensing
- Surface Extraction
- Texture Generation

3D Reconstruction

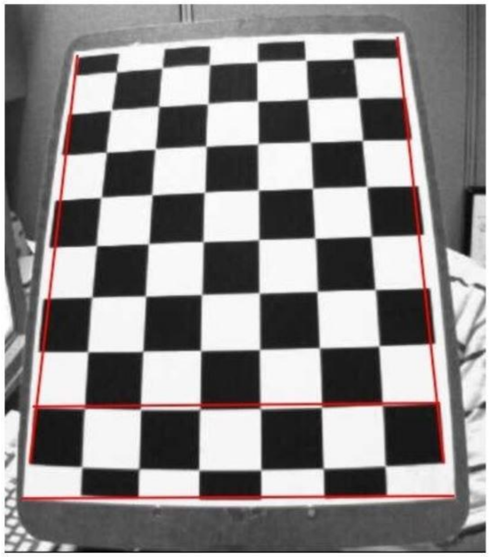
- Camera Calibration
  - Multiple cameras
  - Distortion
  - Intrinsic and extrinsic parameters are different for different cameras



3D Reconstruction Algorithm

- Camera Calibration

- **Input**: set of pictures
- **Output**: camera position, orientation, intrinsic parameters (focal length, optical center)



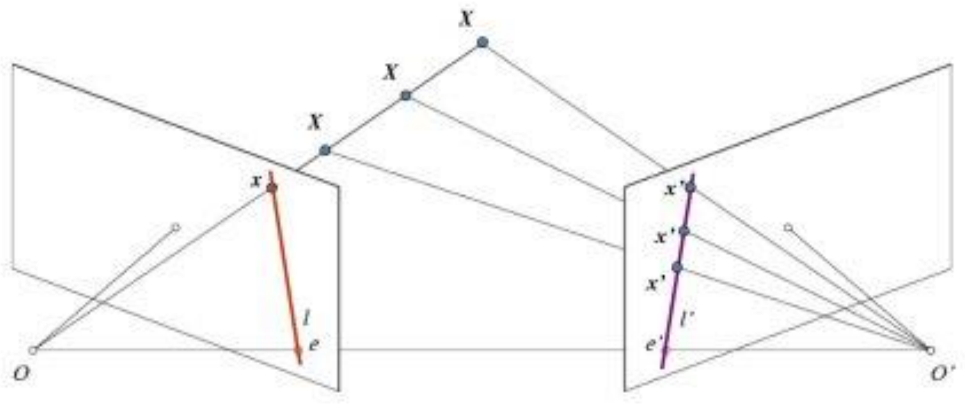
3D Reconstruction Algorithm

- Depth Sensing
  - Input: set of calibrated images
  - Output: distance to object for each pixel in the image

- Popular methods
  - Stereo triangulation
  - Time of flight
  - Structured light projection

3D Reconstruction Algorithm

- Depth Sensing

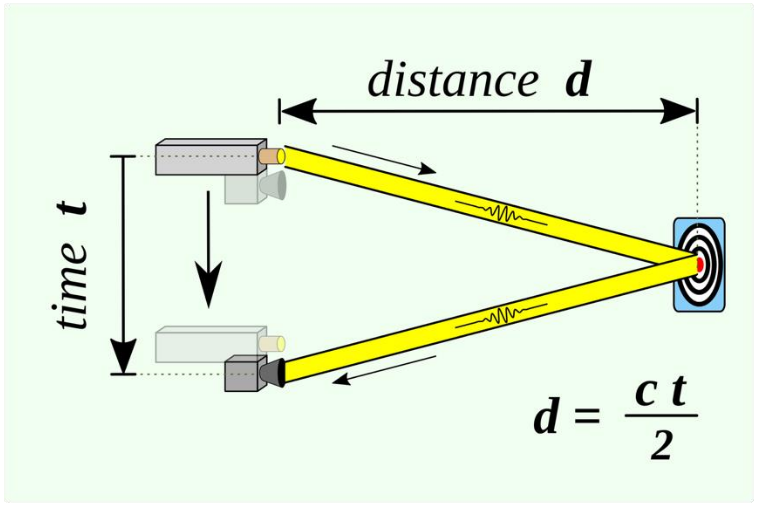


Stereo Triangulation

Zed Camera

3D Reconstruction Algorithm

- Depth Sensing

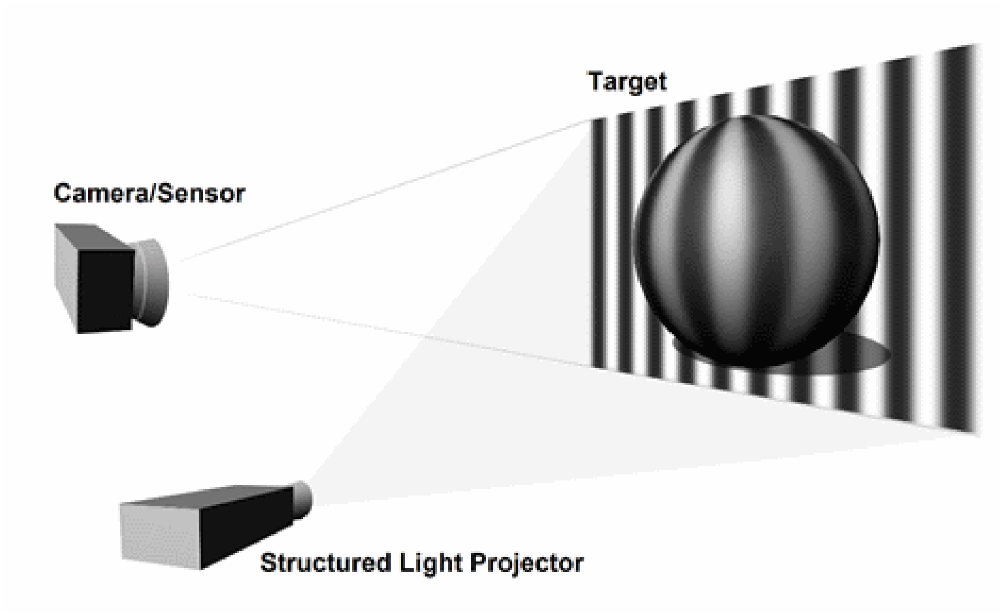


Time of flight

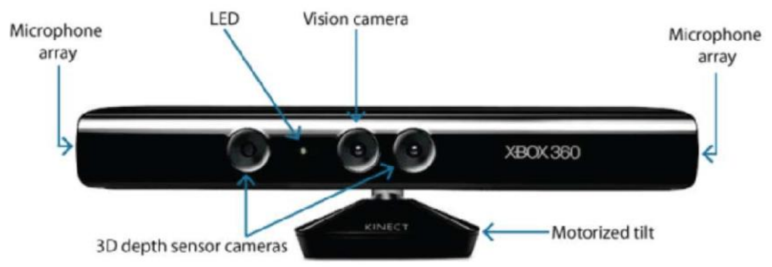
Helios

3D Reconstruction Algorithm

- Depth Sensing



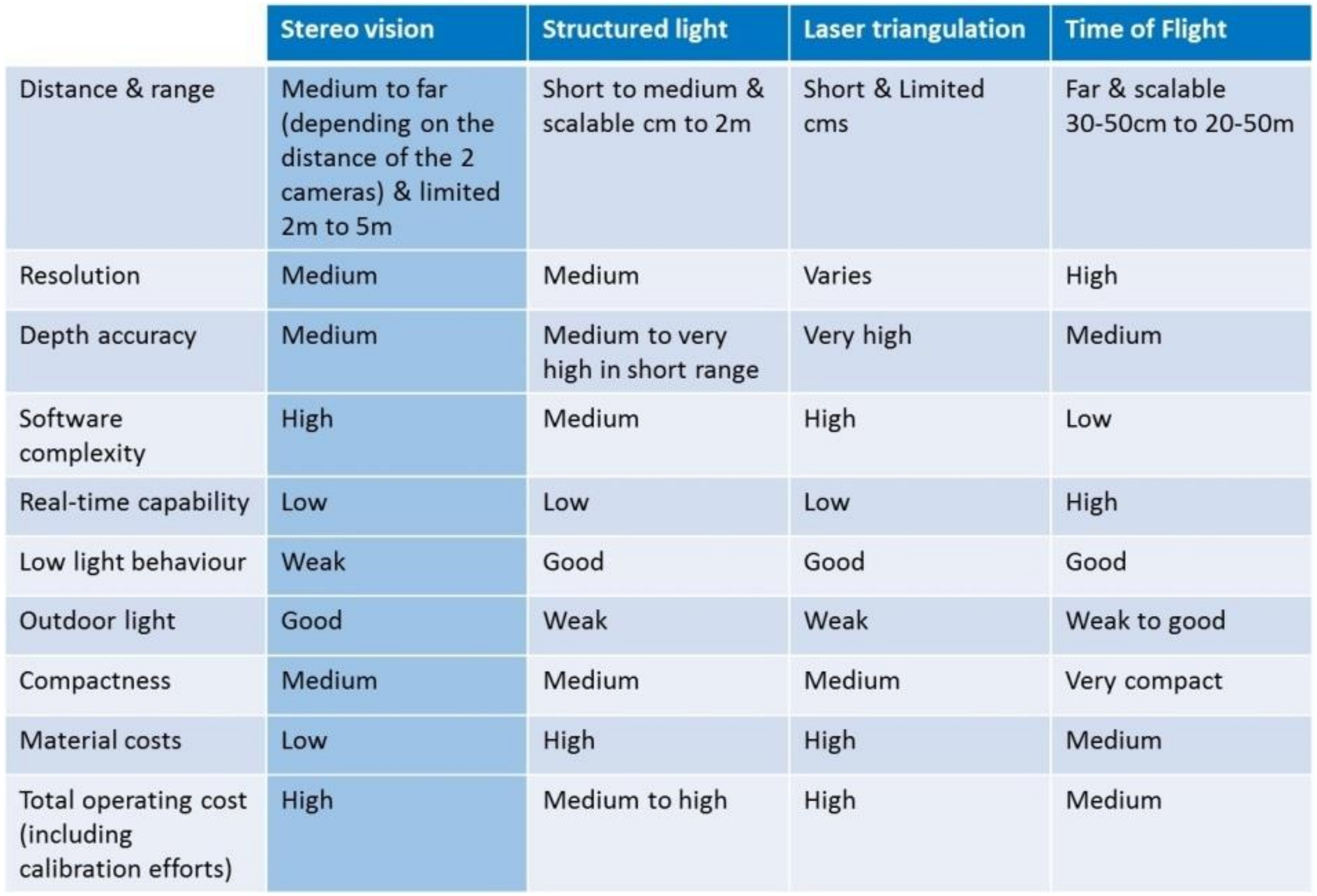
Structured light projection



Azure Kinectv1

3D Reconstruction Algorithm

- Depth Sensing

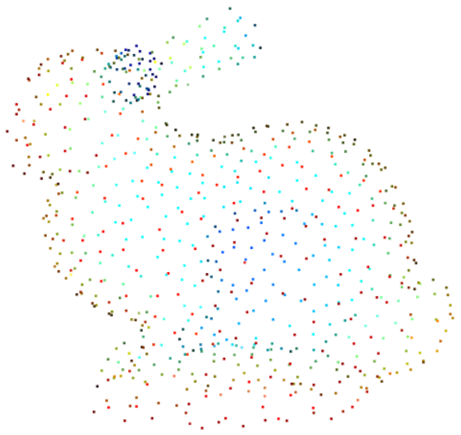


	Stereo vision	Structured light	Laser triangulation	Time of Flight
Distance & range	Medium to far (depending on the distance of the 2 cameras) & limited 2m to 5m	Short to medium & scalable cm to 2m	Short & Limited cms	Far & scalable 30-50cm to 20-50m
Resolution	Medium	Medium	Varies	High
Depth accuracy	Medium	Medium to very high in short range	Very high	Medium
Software complexity	High	Medium	High	Low
Real-time capability	Low	Low	Low	High
Low light behaviour	Weak	Good	Good	Good
Outdoor light	Good	Weak	Weak	Weak to good
Compactness	Medium	Medium	Medium	Very compact
Material costs	Low	High	High	Medium
Total operating cost (including calibration efforts)	High	Medium to high	High	Medium

https://www.azom.com/article.aspx?ArticleID=16003

3D Reconstruction Algorithm

- Surface Extraction from Depth
  - Input: set of calibrated images & depth maps
  - Output: mesh of object



3D Reconstruction

- Texture Generation
  - Input: set of calibrated images and mesh of object
  - Output: atlas and texture

Summary of the Lecture

- Discuss Homework1
- XR Internals
- Sensors
- Sensing Algorithms

Next Up: XR Data Structures