Robotic Mapping & Localization

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Lecture 2: Sensors

*Courtesy of Luca Carlone (MIT)

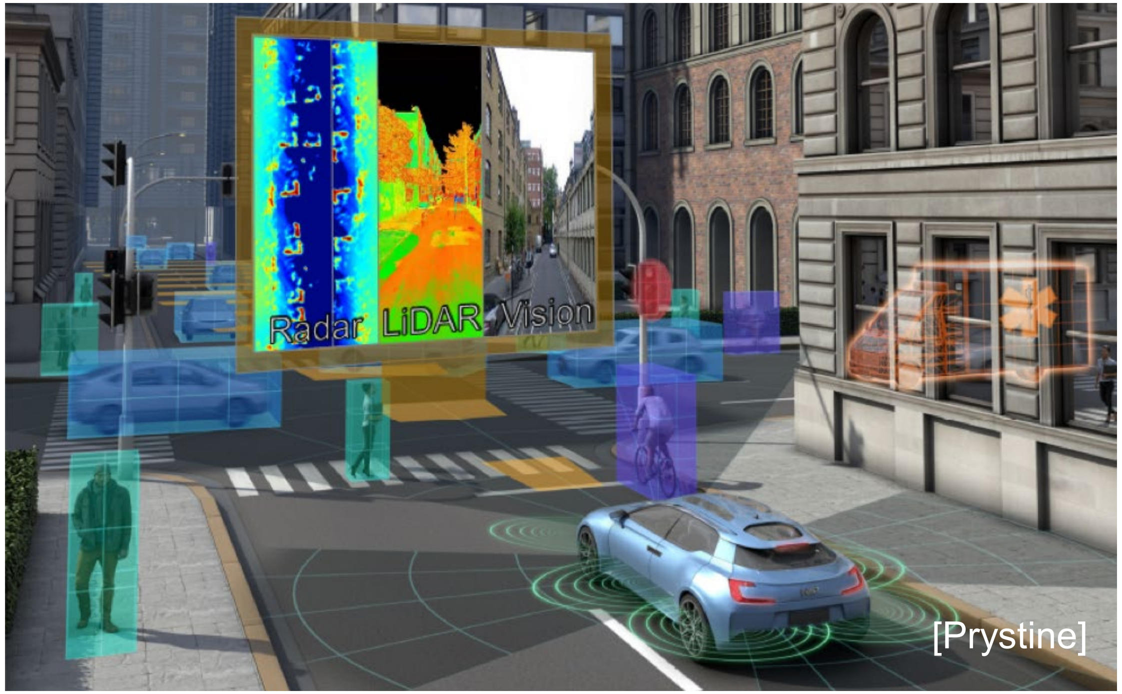
Lecture Outline

- **Topics**
  - Review
  - Sensors
    - Cameras
      - Mono; Stereo/RGB-D; Thermal; Hyperspectral; Event
    - LiDAR
      - 2D/3D; Rotating/Solid-state
    - IMU
    - Radar
    - Sonar/Ultrasonic
    - GPS
      - RTK/differential GPS
    - Misc:
      - Encoder; UWB; Pressure sensors

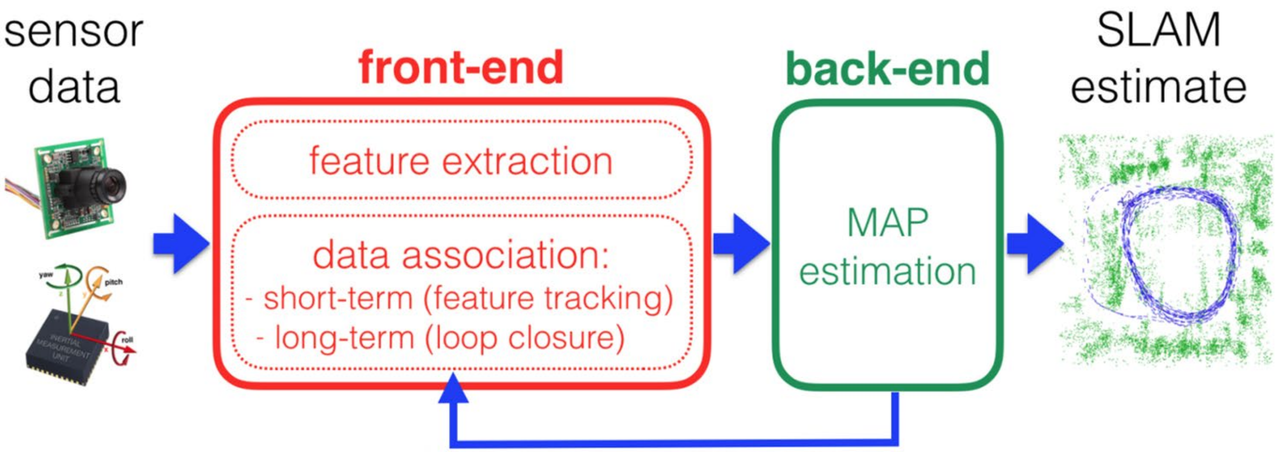
Review

- **SLAM** is simultaneous
  - Localization
  - Mapping

- A SLAM pipeline consists of
  - Sensors
  - Frontend algorithms
  - Backend algorithms



[Prystine]



[Carlone, Visual Nav, MIT]

Cameras

- Cameras are the most commonly used sensors in SLAM/robotics
- Serve as “eyes” of robots

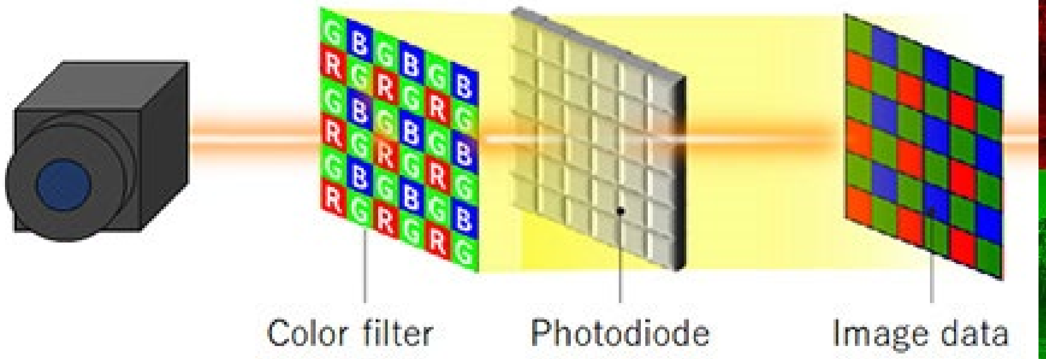
- **Mapping:** Cameras capture visual data to create a map of the environment

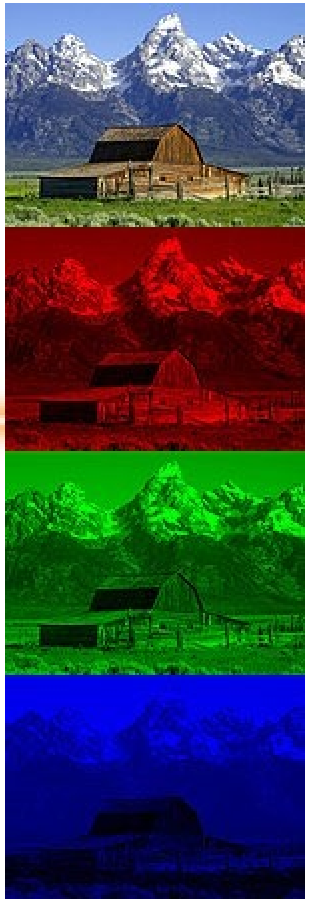
- **Localization:** Cameras aid in determining the robot's position within the mapped environment

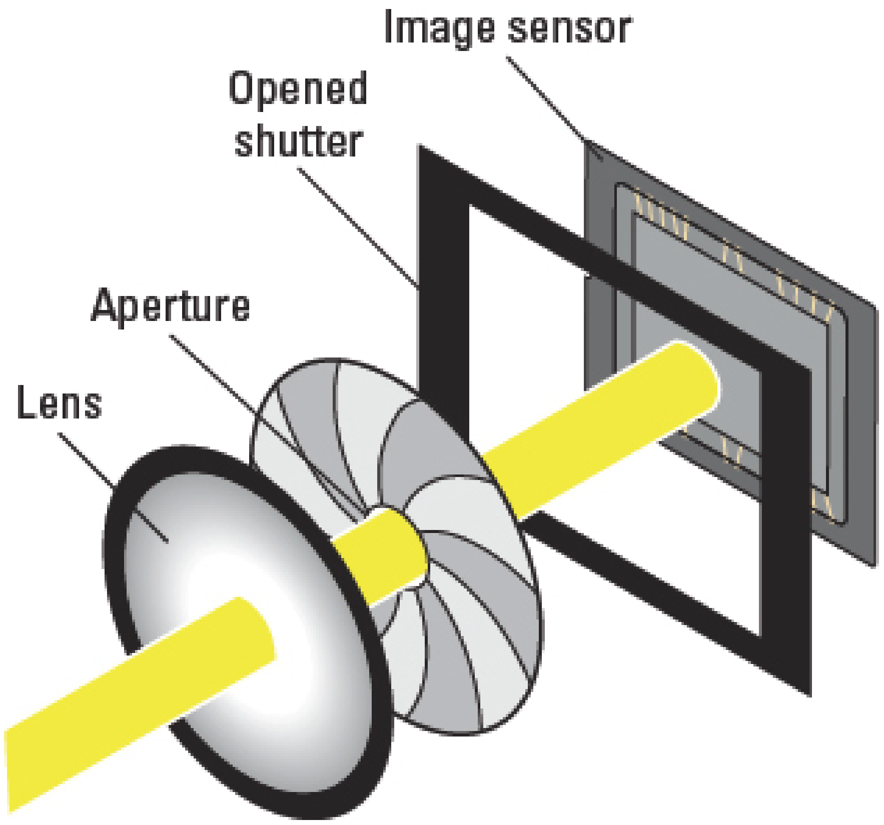
[Photo by Jonathan Lampel]

Cameras

- **Monocular** (mono) or **RGB** cameras capture red, green, and blue spectrums of the visible light
- Key components of a camera are lens, aperture, shutter, image sensor







Cameras

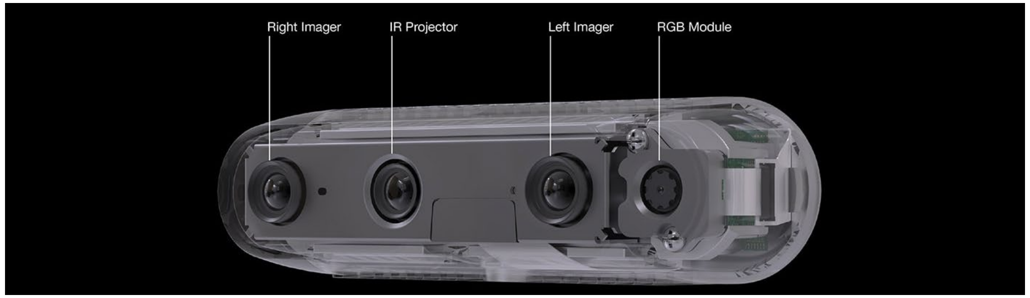
- **Advantages**:
  - Cost-effective, affordable, widely available (vs other sensors)
  - Rich visual data provide detailed info of the environment
  - Small size/weight
- **Challenges**:
  - Poor performance in low-light conditions
  - Motion blur with fast motion
  - High computational need to process (image) data
  - Projective/2D geometry; scale ambiguity

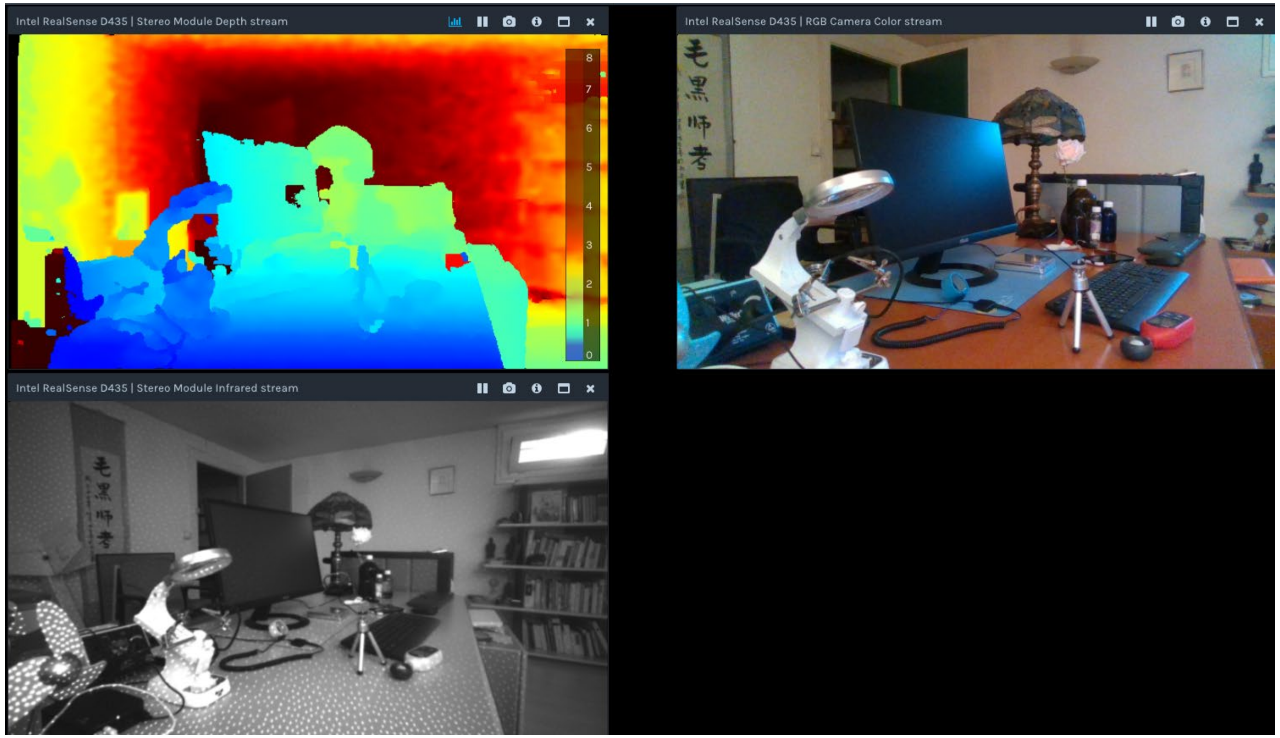
Low-light image

Motion blur

Depth ambiguity

Stereo Cameras

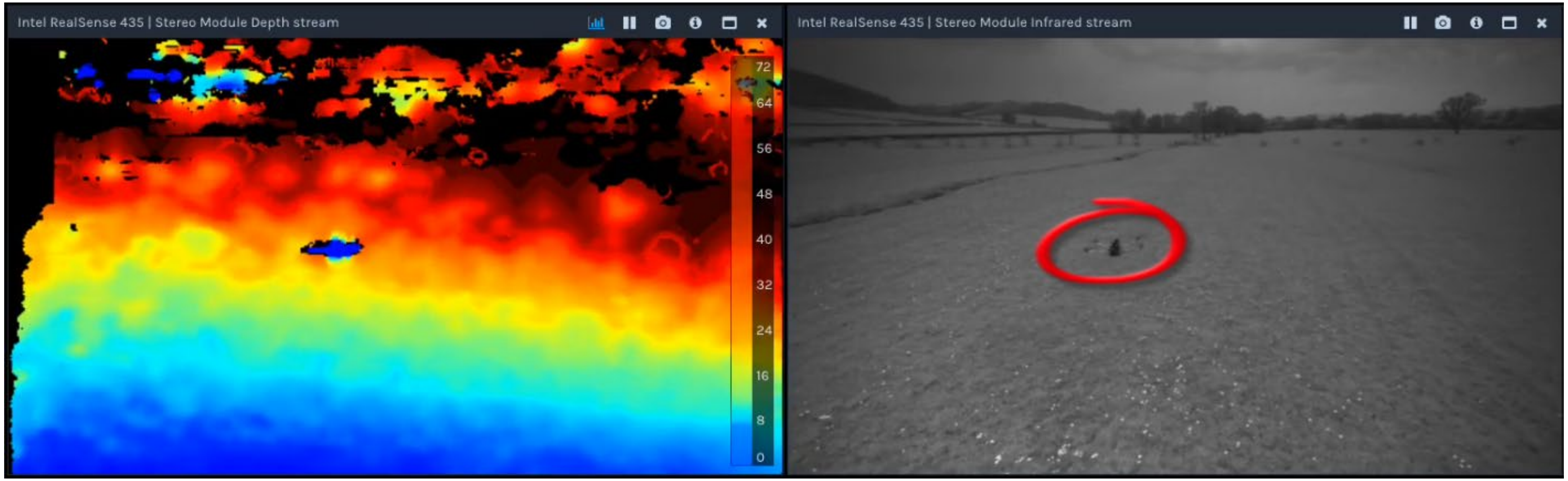




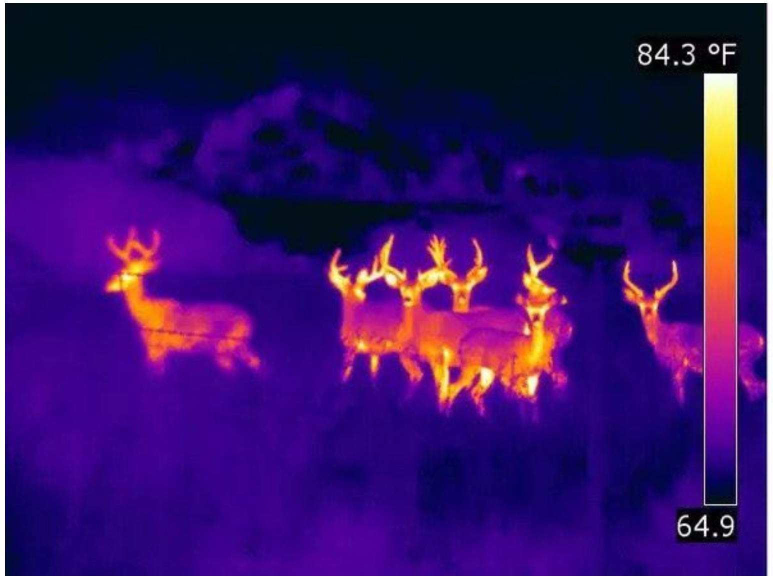
- **Stereo/RGB-D cameras** can create a depth map of the scene (3D model)
- Unlike mono, the scale of the scene is *not* ambiguous
- Stereo cameras rely on disparities between images; Some RGBD cameras have dedicated depth sensors to directly measure distance
- Sometimes use structured (IR) light to help measure distance

Stereo Cameras

- **Advantages**:
  - Depth perception: A dense 3D model of the environment
  - Cost-effective (vs LiDAR)
  - Many commercially-available options ($100-$500)
- **Challenges**:
  - Same issues of mono cameras; IR cameras struggle in bright outdoors
  - Limited range of depth perception (~10 m)
  - Low depth accuracy (vs Lidar); Noisy (“egg-carton” effect)

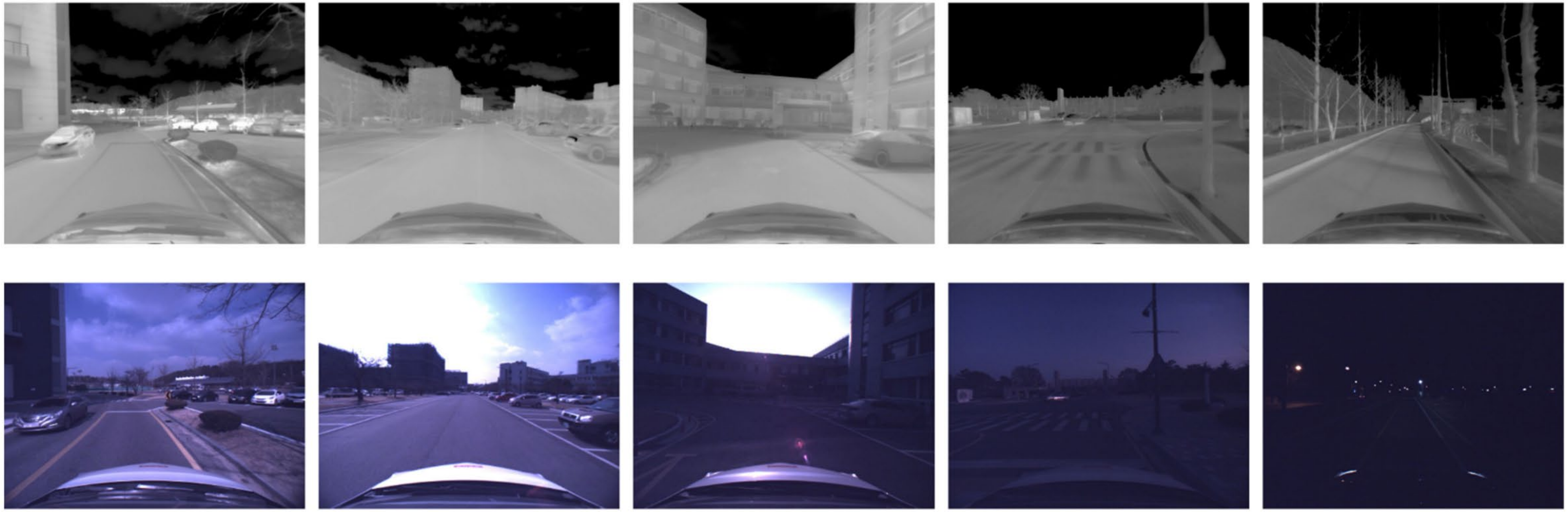


Thermal Cameras



- **Thermal** or **infrared** (IR) cameras capture infrared radiation (heat) emitted by objects
- Camera sensor can be cooled or uncooled
- Uncooled is common in consumer-grade applications; generally more compact & cost-effective
- Cooling mechanism for IR sensor provides higher sensitivity & image quality (for professional/military applications)

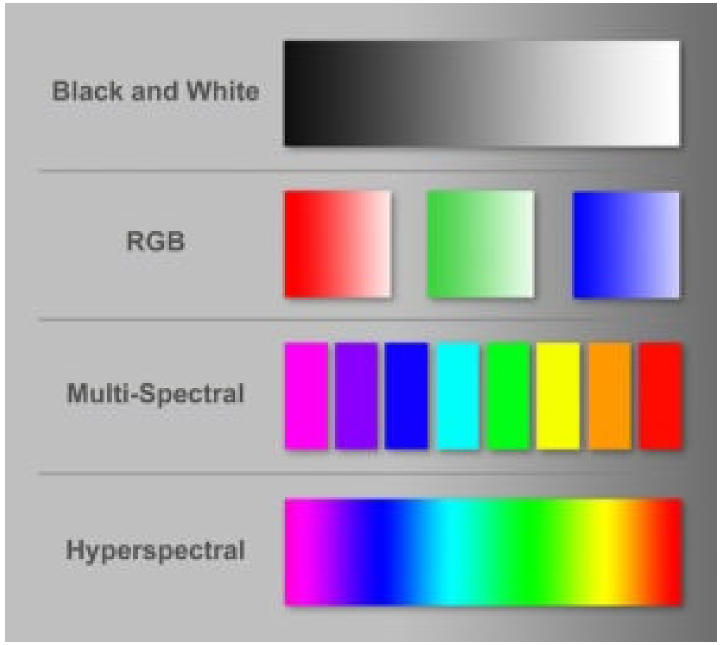
Thermal Cameras

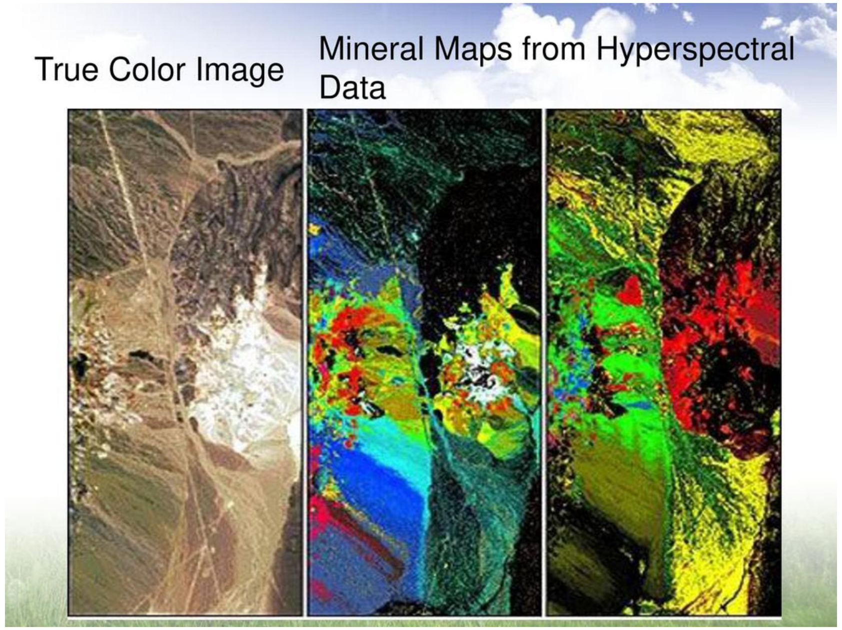


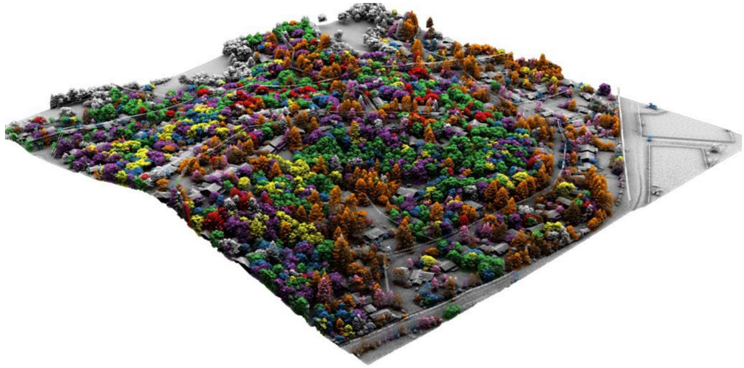
[Shin RAL19]

- **Advantages**:
  - Night vision
  - Can see (better than RGB) in smoke, fog, other atmospheric obscurants
- **Challenges**:
  - Limited detail & lower resolution than RGB
  - More expensive than RGB
  - Can't differentiate between materials with the same temperature

Hyperspectral Cameras

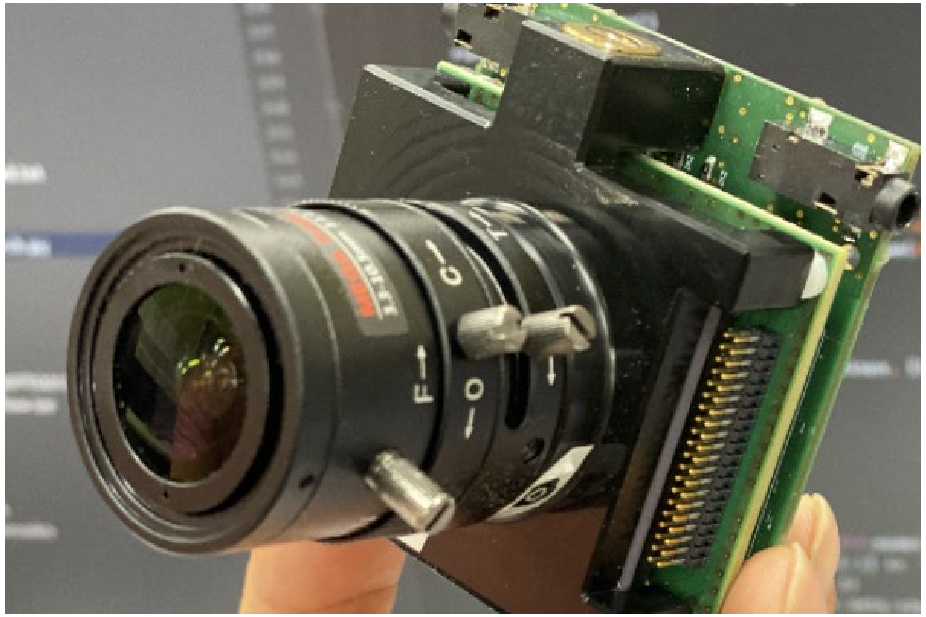


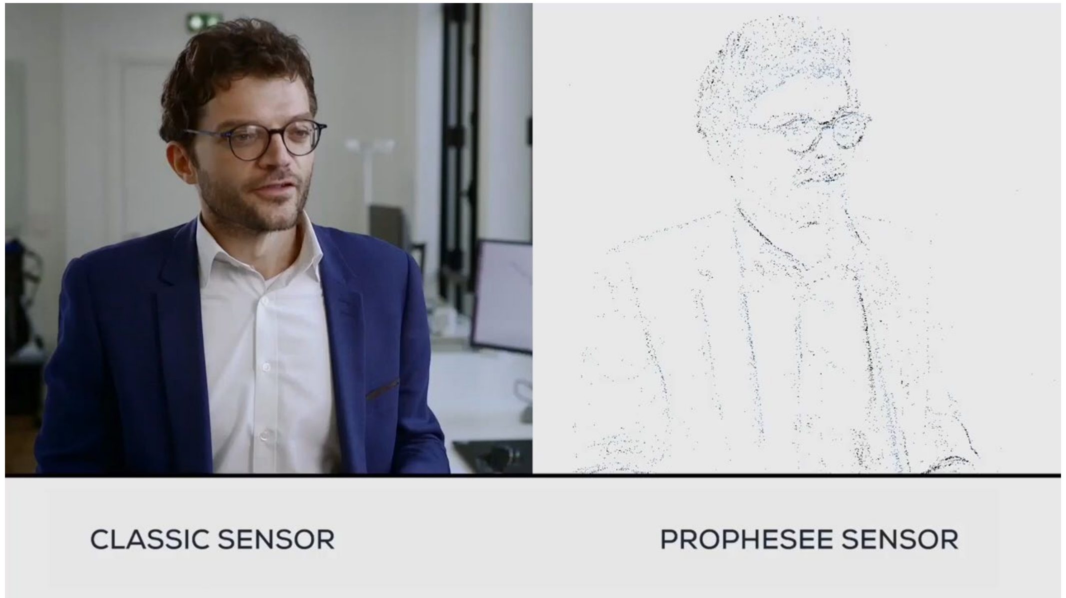




- **Hyperspectral cameras** cover multiple narrow spectral bands (vs RGB)
- Can reveal unique material characteristics
- Particularly useful for agriculture: Crop health monitoring; detecting vegetation (as chlorophyll reflects mid-IR spectrum)
- **Challenges**:
  - Same as RGB; more costly

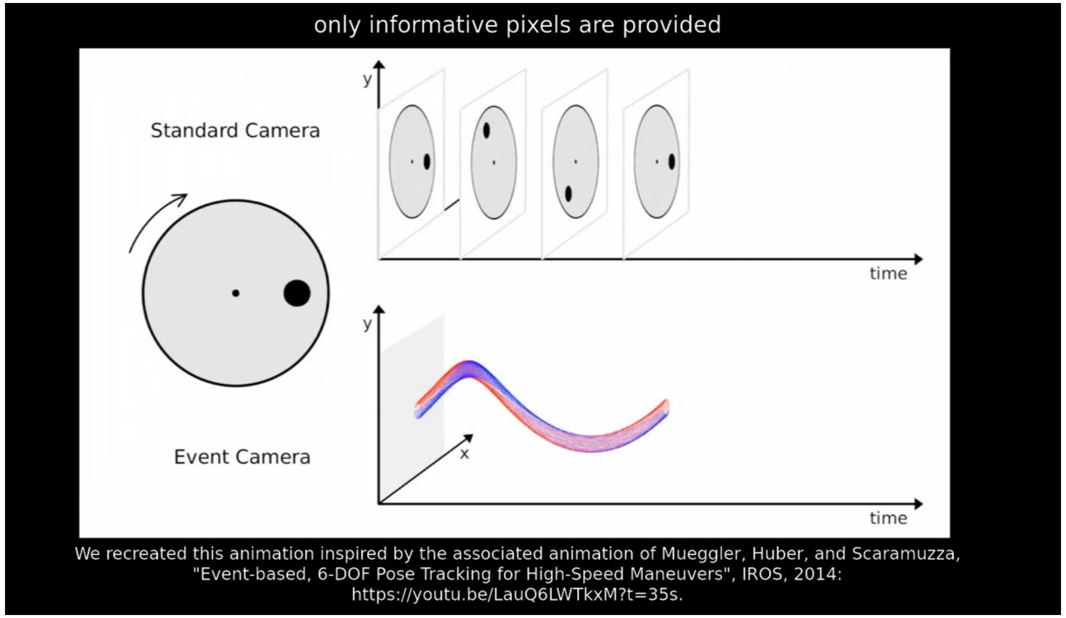
Event Cameras





https://www.youtube.com/watch?v=PLHhEj52c-4

- **Event cameras** capture changes/motion in the Scene
- Unlike traditional cameras, there is no fixed frame rate

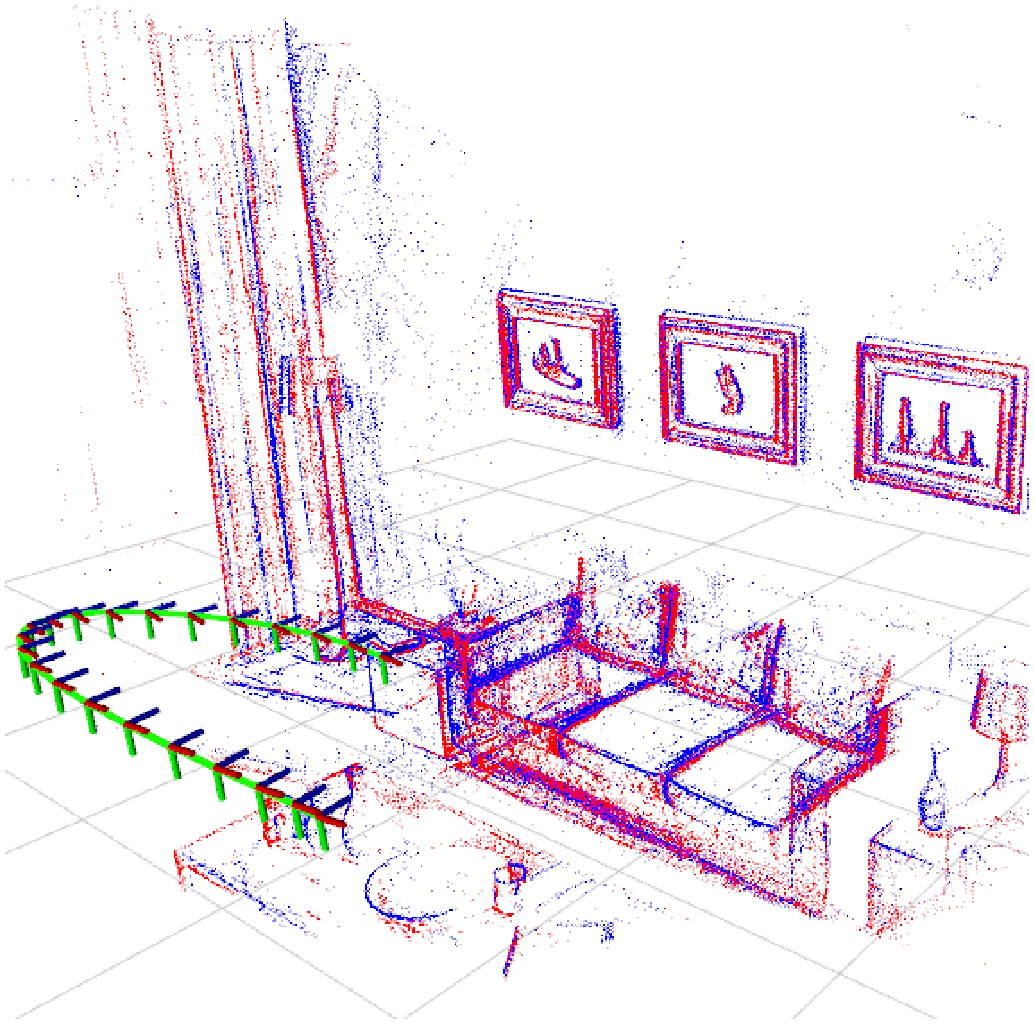


https://www.youtube.com/watch?v=kPCZESVfHoQ

Event Cameras

- **Advantages**:
  - Instantaneous response to events (extremely high framerate)
  - Lower bandwidth requirement (as only changes are transmitted)
  - Good performance in varied lighting conditions

- **Challenges**:
  - Complex data processing
  - Typically very noisy
  - Low/no details of static scenes

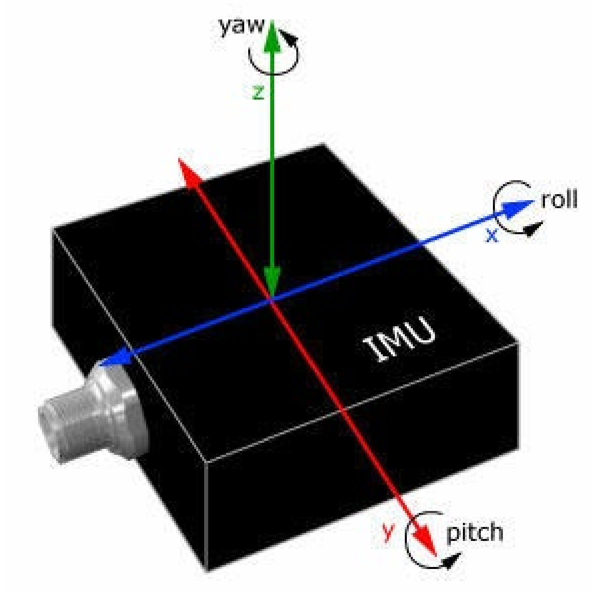


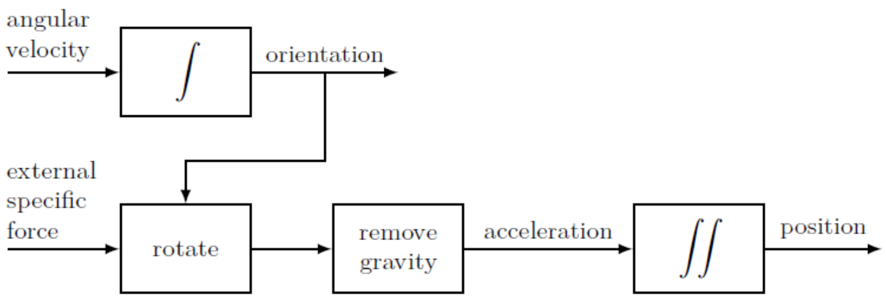
IMU

- An Inertial Measurement Unit (**IMU**) is a proprioceptive sensor

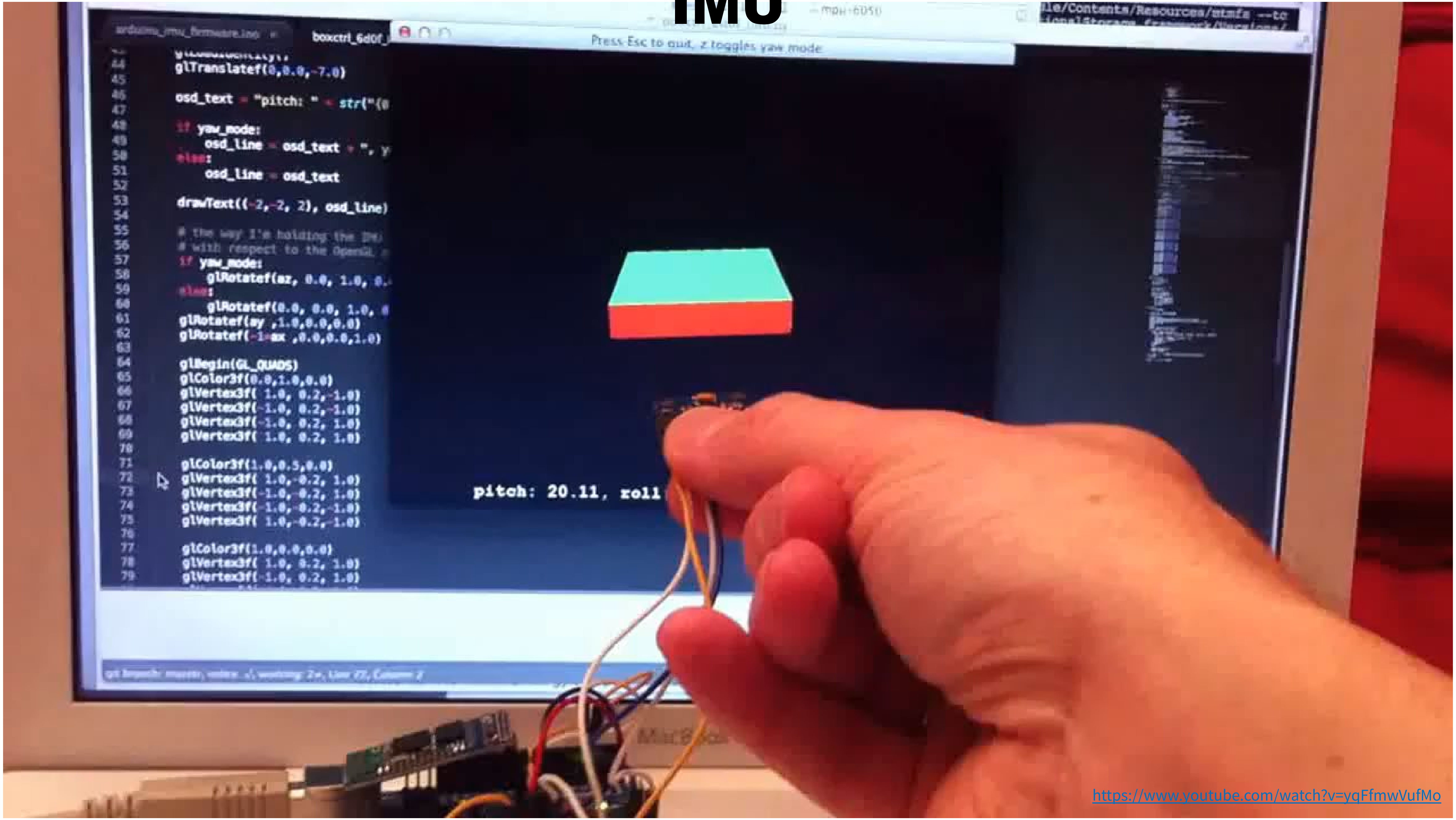
- Components of IMU:
  - **Accelerometer**: Measure linear acceleration
  - **Gyroscope**: Measure angular velocity
  - (sometimes) **Magnetometer**: Measure the strength & direction of magnetic field

- The process of integrating the IMU measurements to get position & orientation estimates is called **dead-reckoning**





IMU



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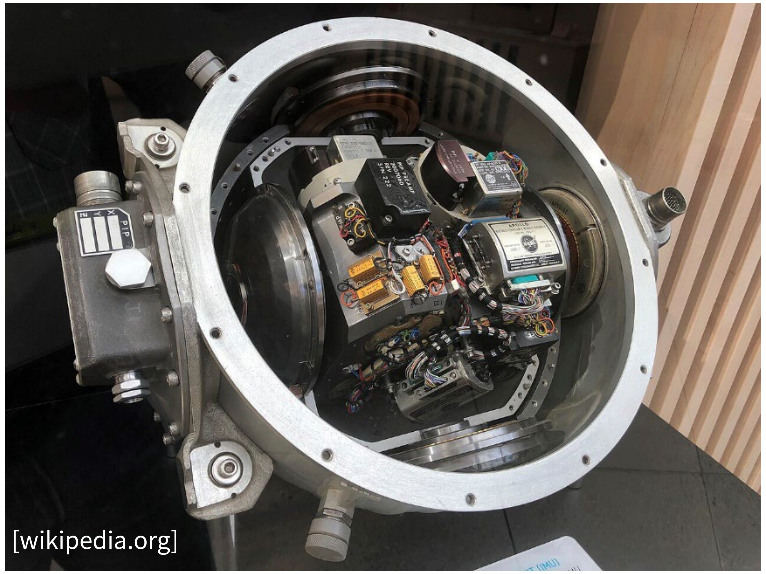
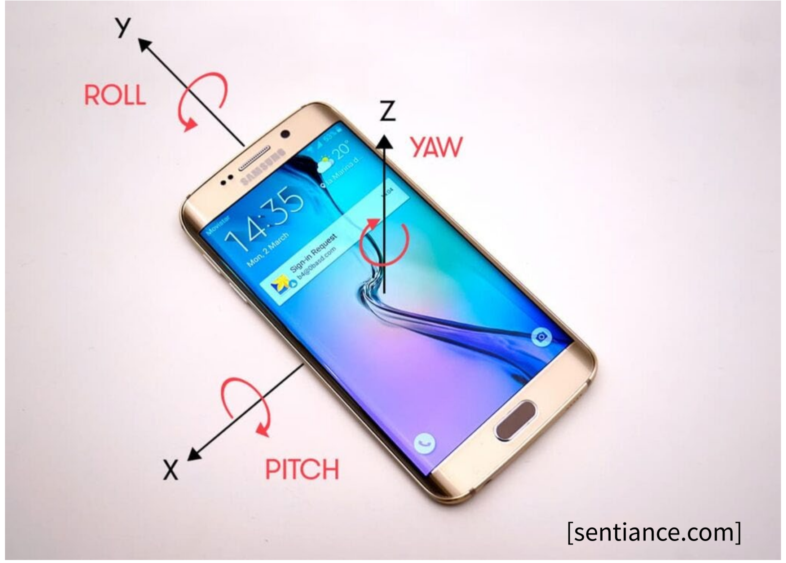
IMU



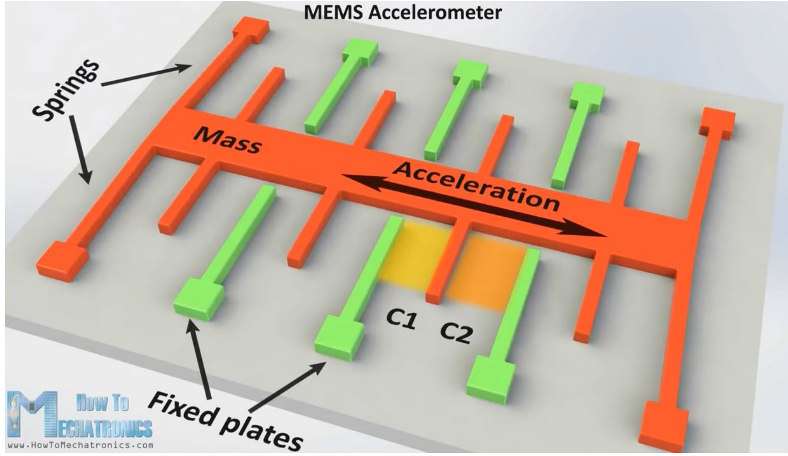
Apollo Inertial Measurement Unit



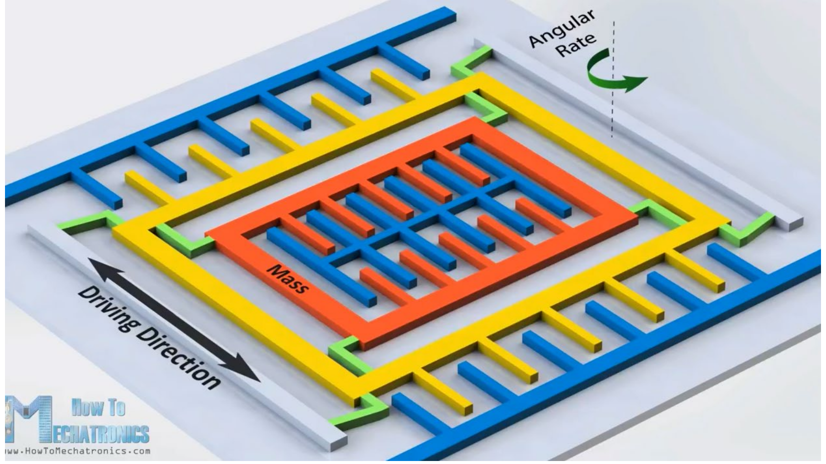
- **Applications**:
  - **Robotics**: Motion estimation for autonomous robots
  - **Aerospace**: Navigation/control of aircraft, drones, missiles
  - **Consumer electronics**: Smartphones, gaming devices, wearables

IMU

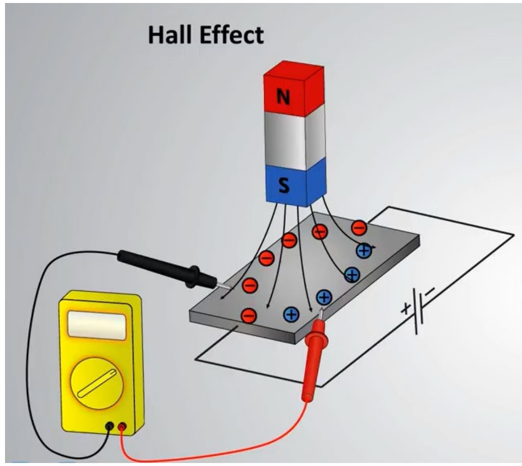
- IMUs can be mechanical or MEMS-based
- MEMS-based IMU working principle:
  - Accelerometer & Gyroscope based on change of capacitance
  - Magnetometer based on Hall effect (induced voltage)



Accelerometer



Gyroscope



Magnetometer

Watch:

- How MEMS Accelerometer Gyroscope Magnetometer Work
  https://www.youtube.com/watch?v=eqZgxR6eRjo

- How a Smartphone Knows Up from Down
  https://www.youtube.com/watch?v=KZVgKu6v808

IMU

[honeywell.com]

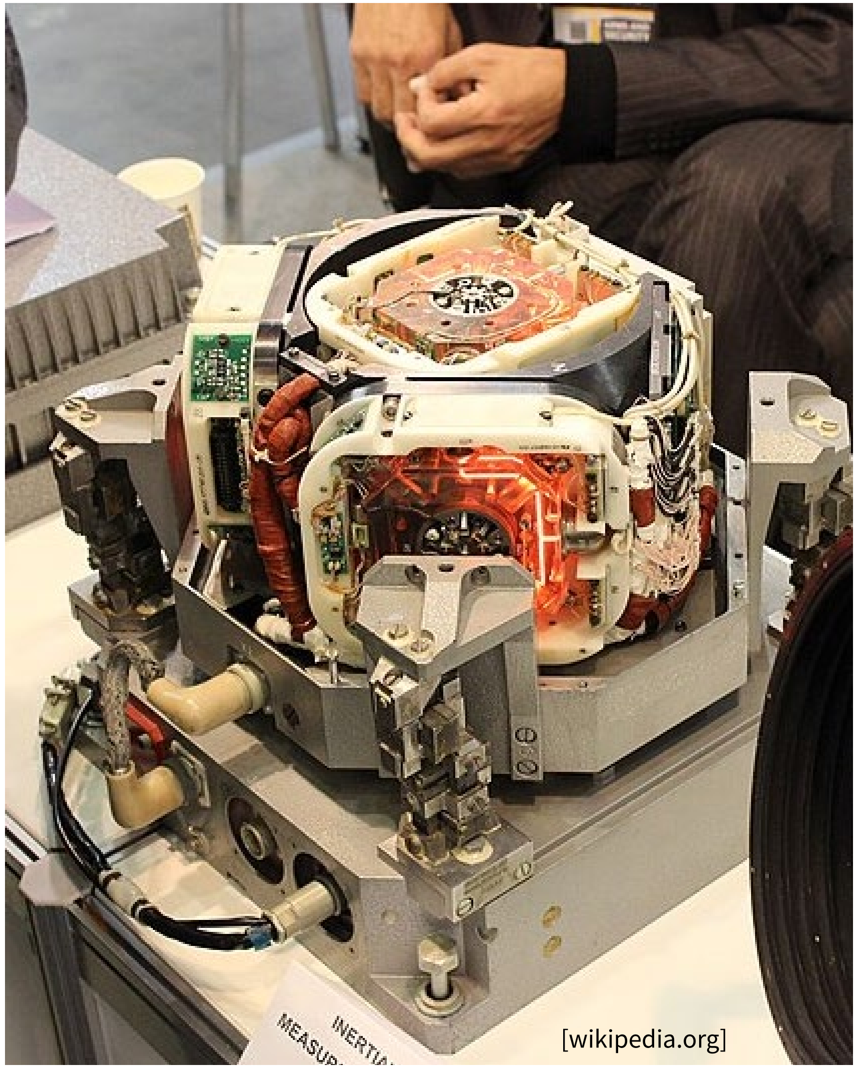
	HG1125 IMU	HG1126 IMU	i300 IMU	HG4930 IMU	HG1930 IMU HG1930 INS	HG1936 RATE SENSOR	HG1900 IMU	HG1700AG IMU	HG1700SG IMU	HG5700 IMU HG5720 INS HG5710 INS	HG9900 IMU
TYPE	High Performance MEMS IMU	High Performance MEMS IMU	High Performance MEMS IMU	High Performance MEMS IMU	High Performance MEMS IMU	High Performance MEMS IMU	MEMS Based Tactical Grade IMU	MEMS Based Tactical Grade IMU	RLG Based Tactical Grade IMU	RLG Based Navigation Grade IMU	RLG Based Navigation Grade IMU
BIAS PERFORMANCE In-run Gyro, Accel Turn-on Gyro, Accel	7 deg/hr, 0.35 mg, 120 deg/hr, 1,5 mg	7 deg/hr, 0.35 mg, 120 deg/hr, 1,5 mg	Typical Performance: 3 deg/hr, 0.02 mg, 65 deg/hr, 2 mg	Typical Performance: 0.25 deg/hr, 0.0025 mg, 7 deg/hr, 1.7 mg	1 deg/hr, 0.3 mg, 20 deg/hr, 5 mg	1.5 deg/hr, 20 deg/hr	1 deg/hr, 0.3 mg 10 deg/hr, 1 mg	0.25 deg/hr, 0.05 mg 1 deg/hr, 1 mg	0.25 deg/hr, 0.05 mg 1 deg/hr, 1 mg	0.01 deg/hr, 0.035 mg 0.035 deg/hr, 0.2 mg	0.0006 deg/hr, 0.010 mg 0.004 deg/hr, 0.025 mg
ANGULAR RANDOM WALK	0.300°/√ hr	0.300°/√ hr	Typical Performance: 0.15°/√ hr	Typical Performance: 0.04°/√ hr	0.125°/√ hr	0.125°/√ hr	0.060°/√ hr	0.125°/√ hr	0.125°/√ hr	0.006°/√ hr	0.002°/√ hr
EXPORT CLASSIFICATION	Non-ITAR (7A994)	Non-ITAR (7A003.d)	Non-ITAR (7A994)	Non-ITAR (7A994)	Non-ITAR (7A003.d) HG1930 INS ITAR	Non-ITAR (7A003.d)	Non-ITAR (7A003.d)	Standard: Non-ITAR (7A003.d) Radiation Tolerant: ITAR	Standard: Non-ITAR (7A003.d) Radiation Tolerant: ITAR	5700: Non-ITAR (7A003.d) 5720: Non-ITAR (7A003.d) 5710: ITAR	Non-ITAR (7A003.d)
SWAP	0.6 in^3 0.06 lbs 0.5 W	0.6 in^3 0.06 lbs 0.5 W	1 in^3 0.08 lbs 0.5 W	5 in^3 0.3 lbs 2 W	5 in^3 0.35 lbs 3 W	5 in^3 0.31 lbs 3 W	17 in^3 1.1 lbs 3 W	33 in^3 2 lbs 5 W	27 in^3 1.5 lbs 5 W	45 in^3 3 lbs 10 W	103 in^3 6 lbs 10 W
STATUS	Production	Development	Production	Production	Production	Production	Production	Production	Production	Production (IMU) Development (INS)	Production

- **IMU grades**:
  - **Consumer**: cell phones ; < $100
  - **Industrial**: vehicles & robotics; $100 - $1,000
  - **Tactical**: military & robotics; $5,000 - $25,000
  - **Navigational**: commercial airlines, satellites, space; > $100,000

IMU

- **Performance ranging**:
  - From 0.1°/s to 0.001°/h for gyroscope
  - From 100 mg to 10 μg for accelerometers

- Rough idea for accelerometer error:
  - At 100 mg, loses its ability to give 50-meter accuracy after around 10 seconds,
  - At 10 μg, loses its 50-meter accuracy after around 17 minutes

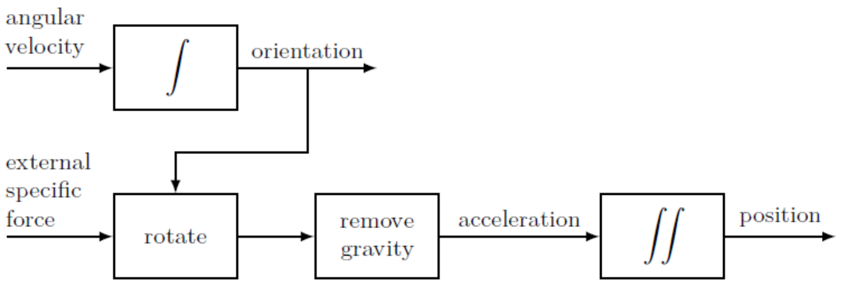


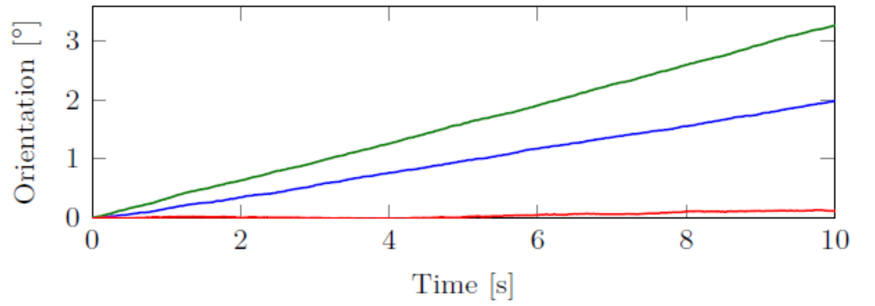
Spacecraft IMU produced by Arsenal factory, Kyiv, Ukraine

IMU

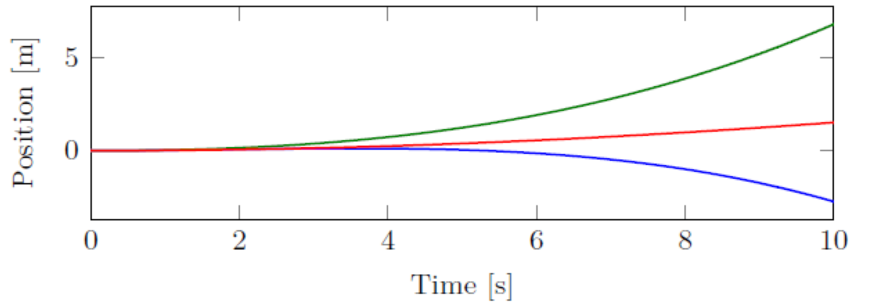
- **Advantages**:
  - Proprioceptive (work in any environment)
  - Small size/weight
  - High measurement rate (1,000 Hz common) can capture fast motion

- **Challenges**:
  - Motion estimates ***drift*** due to (unobservable) biases & noise
  - Sensitive to vibration, temperature change, magnetic interference
  - High quality IMUs are expensive





(a) Integrated orientation for the position in x- (blue), y- (green) and z-direction (red).

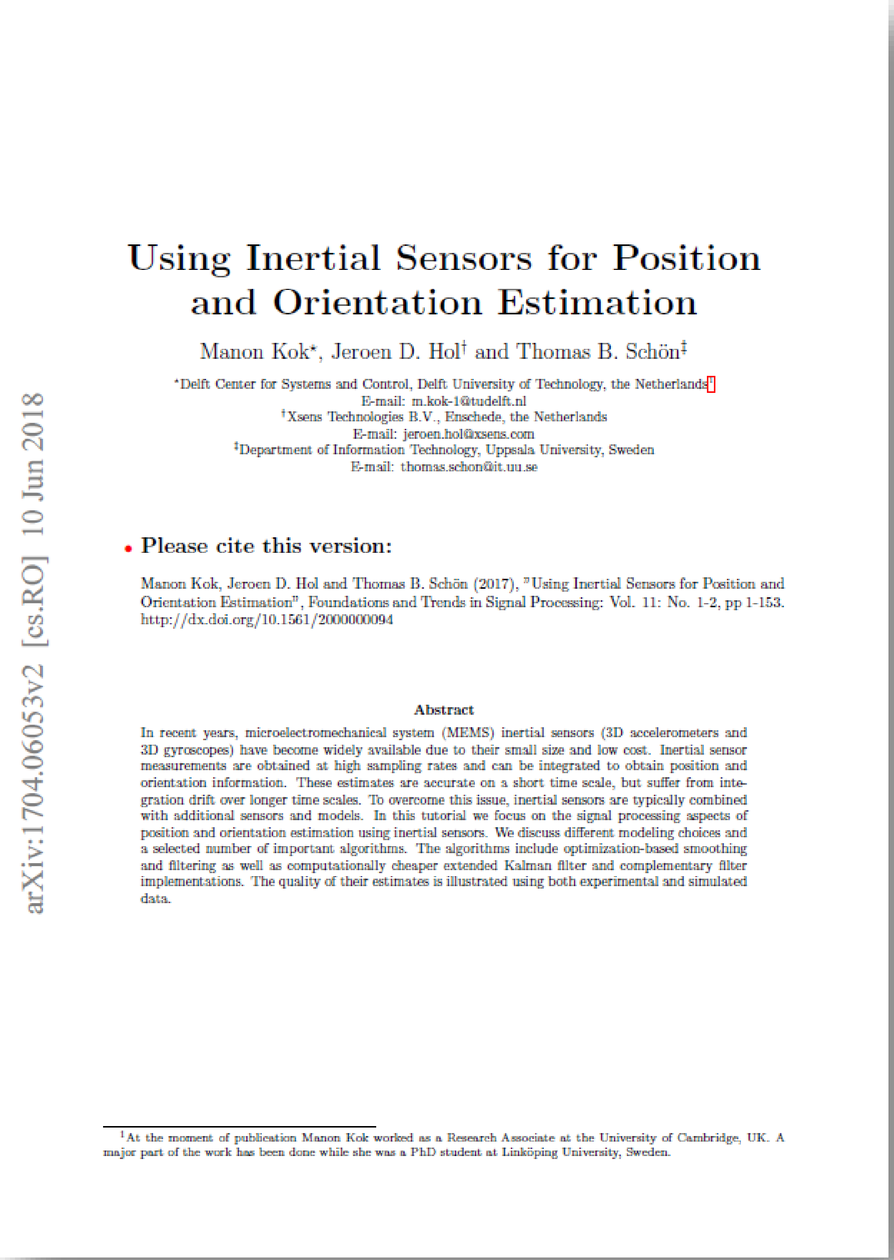


(b) Integrated position for rotation around the x-axis (blue), the y-axis (green) and the z-axis (red).

Position & orientation estimates based on dead-reckoning using a Sony Xperia Z5 Compact smartphone that is lying stationary on a table [Kok17]

IMU

- **Reference:**
  - Tutorial on position and orientation estimation using inertial sensors:



arXiv:1704.06053v2 [cs.RO] 10 Jun 2018

Using Inertial Sensors for Position and Orientation Estimation

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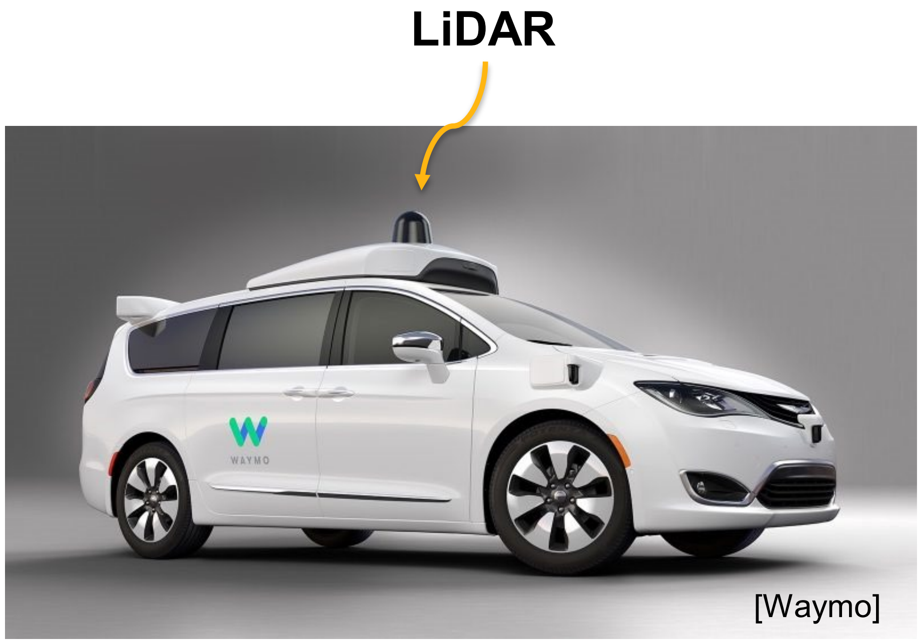
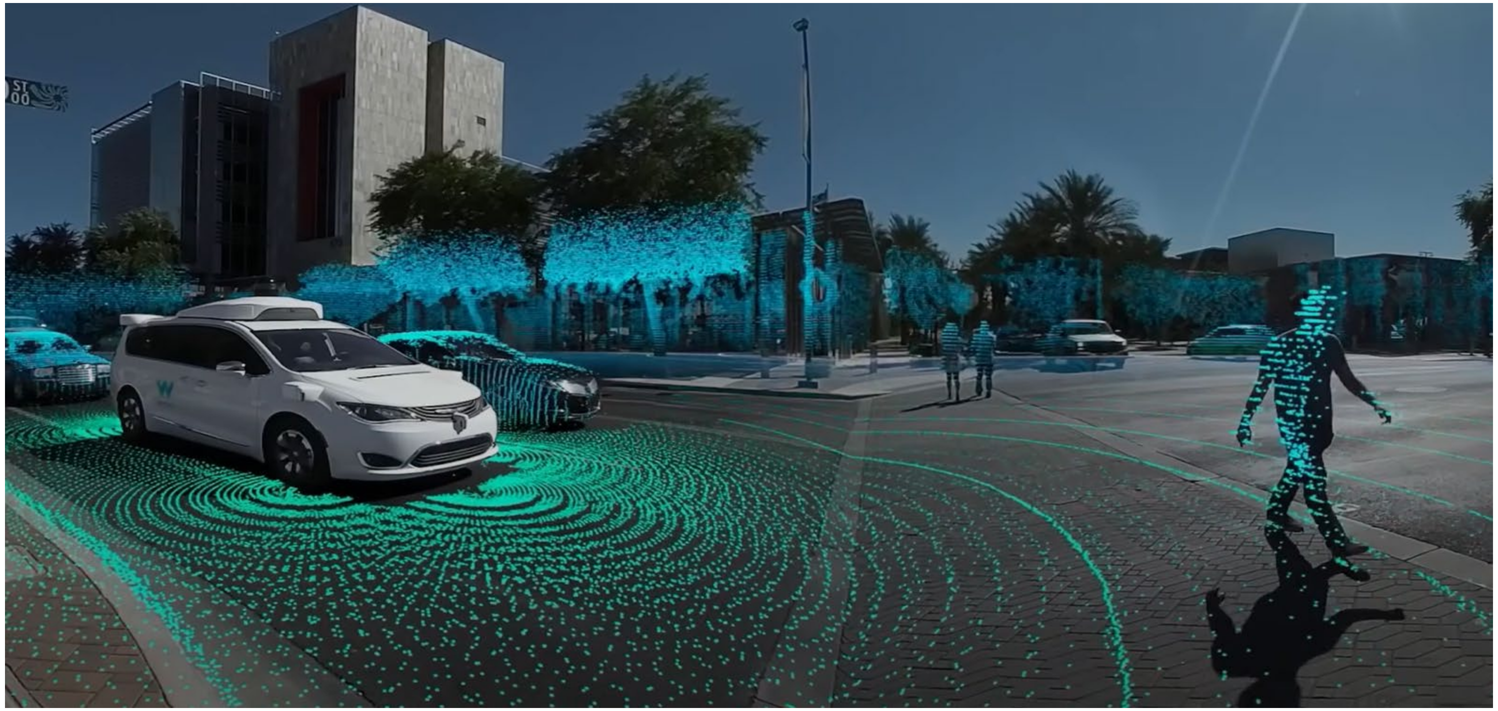
Abstract

In recent years, microelectromechanical system (MEMS) inertial sensors (3D accelerometers and 3D gyroscopes) have become widely available due to their small size and low cost. Inertial sensor measurements are obtained at high sampling rates and can be integrated to obtain position and orientation information. These estimates are accurate on a short time scale, but suffer from integration drift over longer time scales. To overcome this issue, inertial sensors are typically combined with additional sensors and models. In this tutorial we focus on the signal processing aspects of position and orientation estimation using inertial sensors. We discuss different modeling choices and a selected number of important algorithms. The algorithms include optimization-based smoothing and filtering as well as computationally cheaper extended Kalman filter and complementary filter implementations. The quality of their estimates is illustrated using both experimental and simulated data.

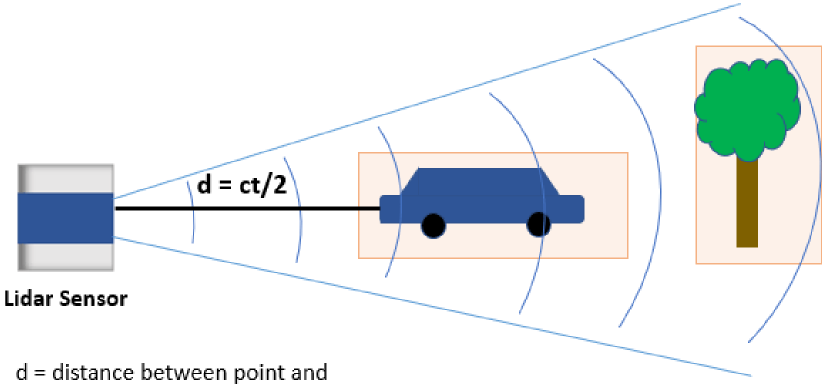
[1] At the moment of publication Manon Kok worked as a Research Associate at the University of Cambridge, UK. A major part of the work has been done while she was a PhD student at Linköping University, Sweden.

LiDAR





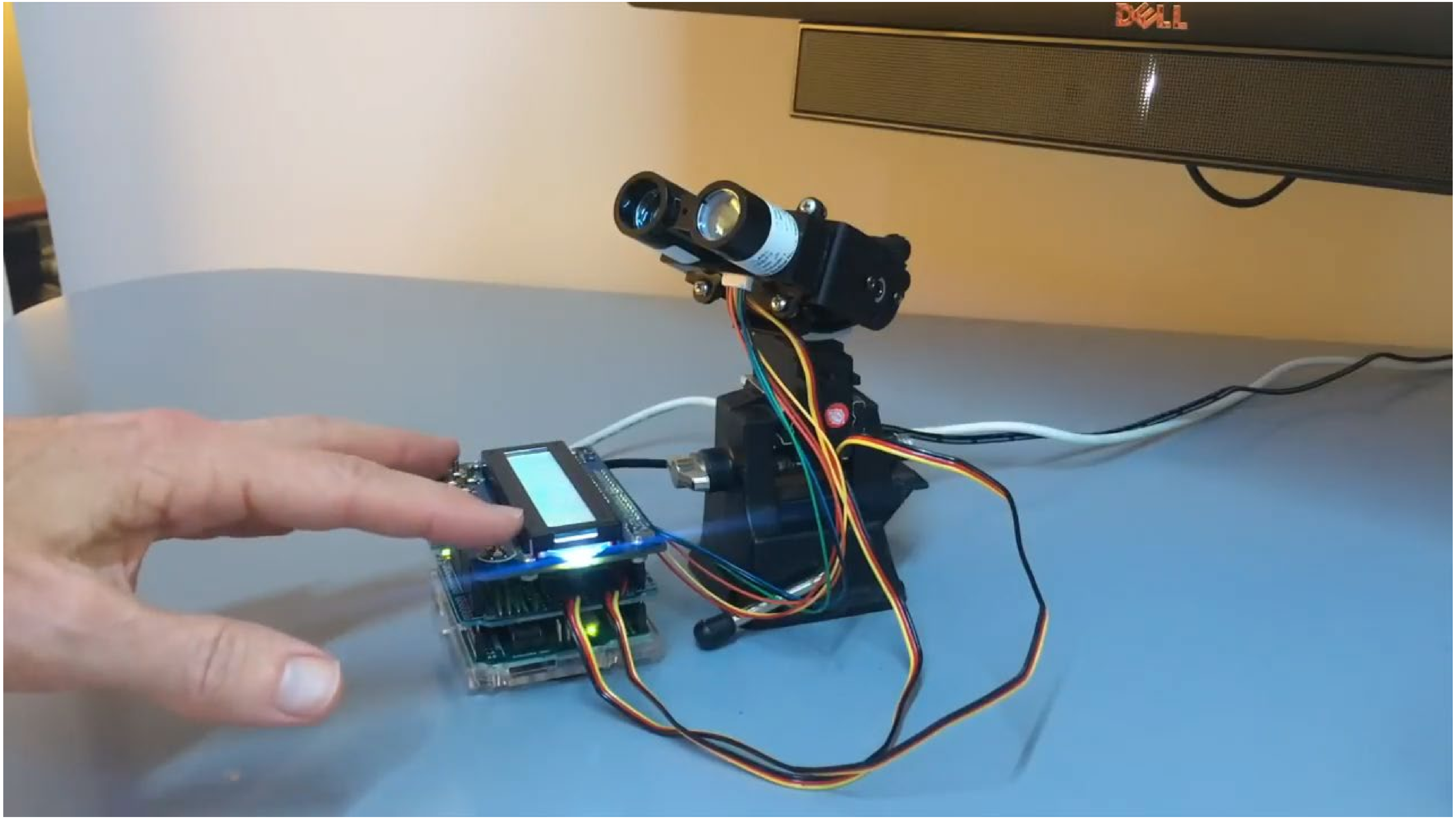
- Light Detection and Ranging (**LiDAR**) is an exteroceptive sensor
- LiDAR calculates how long it takes for beams of light to hit an object & reflect back to the sensor ➔ distance to the object



d = distance between point and the sensor
c = speed of light
t = time of flight

LiDAR

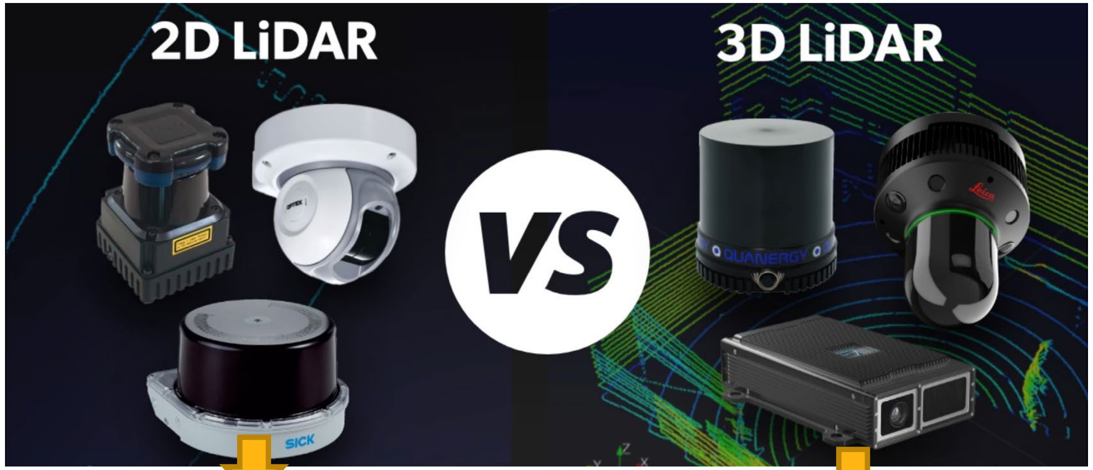
https://www.youtube.com/watch?v=xkut3yRL61U

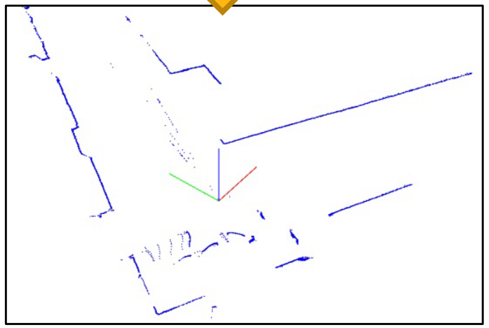


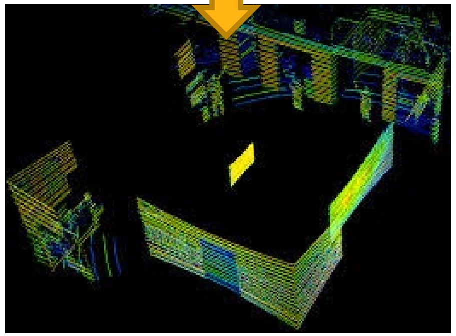
LiDAR

- Common LiDAR sensors provide 2D or 3D scans

- Lidars can be rotating vs. solid state
- In a rotating/spinning LiDAR, a laser beam is steered at 360° by a mechanical system
- In a solid-state LiDAR, a MEMS-based mirror vibrates to scan the environment







Rotating

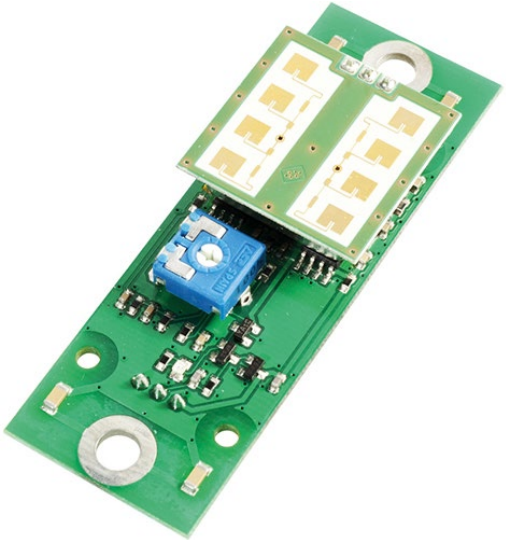
Solid-state

LiDAR

Ford tests Lidar-equipped car in pitch darkness [techcrunch.com]

- **Advantages**:
  - Works day/night
  - Very high accuracy
  - Provides 3D/depth information; detailed 3D maps
  - Operates effectively over long distances
- **Challenges**:
  - Poor performance in (heavy) rain, snow, fog, dusty conditions (due to spurious beam returns)
  - Surfaces with low reflectivity (e.g., black/dark surfaces) may be challenging to detect
  - Traditional (spinning) LiDAR sensors are heavy; high power consumption
  - More expensive than alternative sensors (e.g., RGBD cameras)
  - Crosstalk from other LiDAR devices

Radar



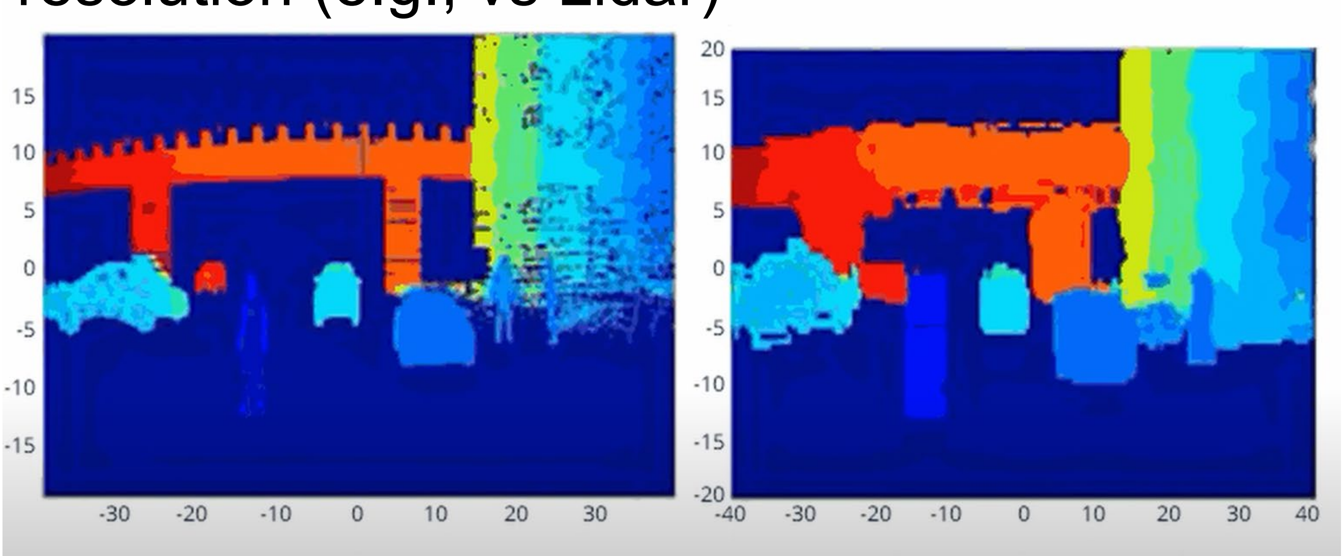
SAR image of Pentagon [Crockett'13]

- **RADAR** (Radio Detection and Ranging) sensors use radio waves
- Transmitter sends radio waves
- Wavelength determines detection range
- Receiver processes echo signals received by the antenna
- Synthetic Aperture Radar (SAR) is used widely in remote sensing to creates high-res images

Radar

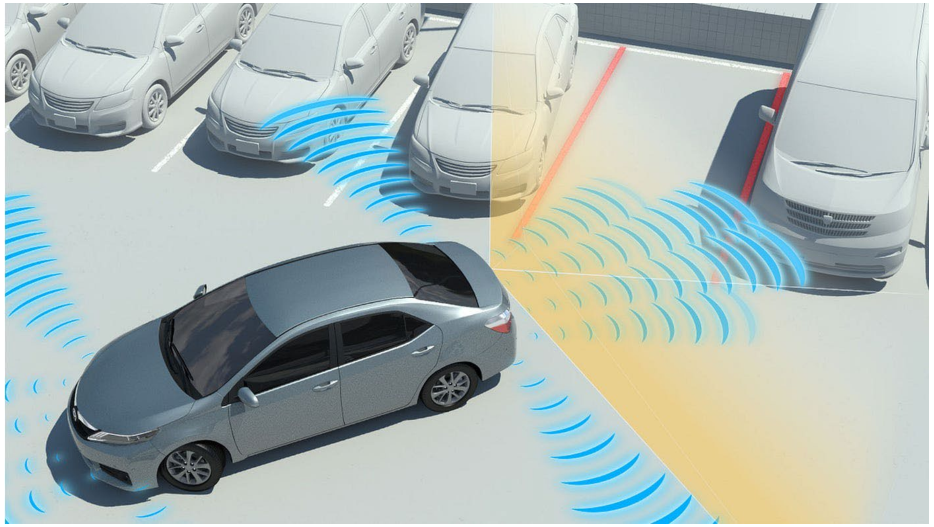
- **Advantages**:
  - Works day/night
  - All-weather operation: rain, fog, snow
  - Unaffected by visual obstructions
  - Long-range detection over extensive distances (used for satellite surveillance)
- **Challenges**:
  - Requires complex data processing
  - High-quality radar sensors are expensive
  - Do not provide details about composition or surface properties
  - Limited spatial resolution (e.g., vs Lidar)

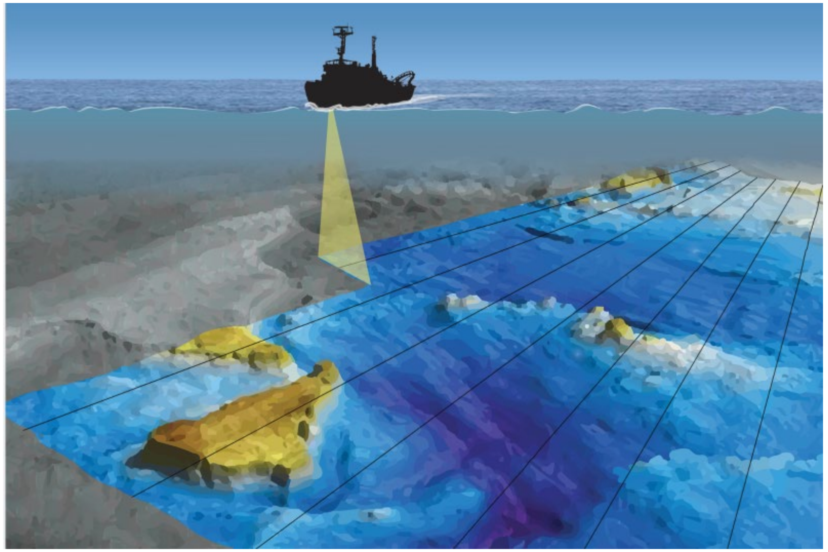
Lidar ➔



🡐 Radar

Sonar/Ultrasonic





- **Sonar** (Sound Navigation and Ranging) works by acoustic sensing through sound waves
- Principle is "echolocation", i.e., emitting sound waves (pings) and measuring time for echo return
- Sonar operates at lower frequencies; primarily associated with underwater applications
- Ultrasonic sensors operate at higher frequencies (> 20 kHZ) and work in air or other gases

Sonar/Ultrasonic

(b)

[Fallon, Ocean Eng'13]

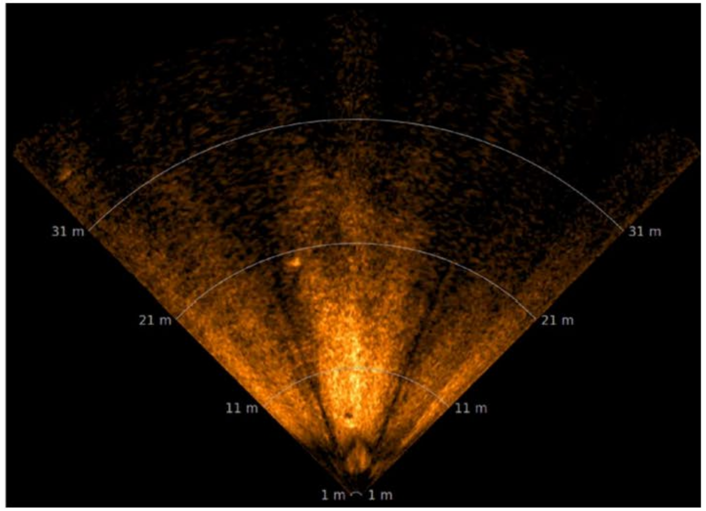
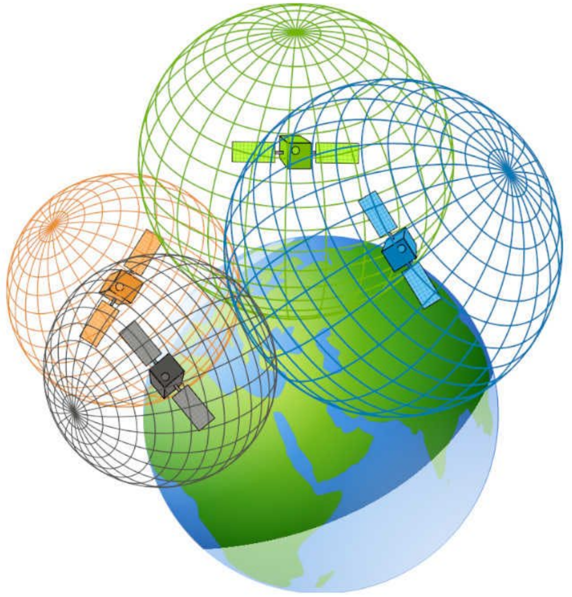
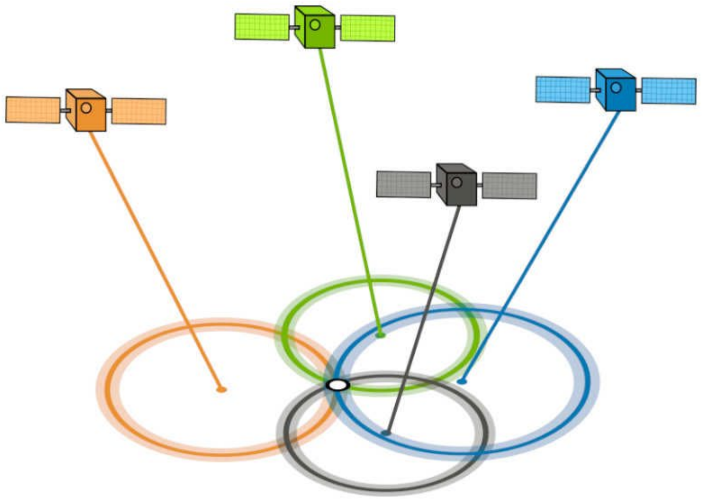


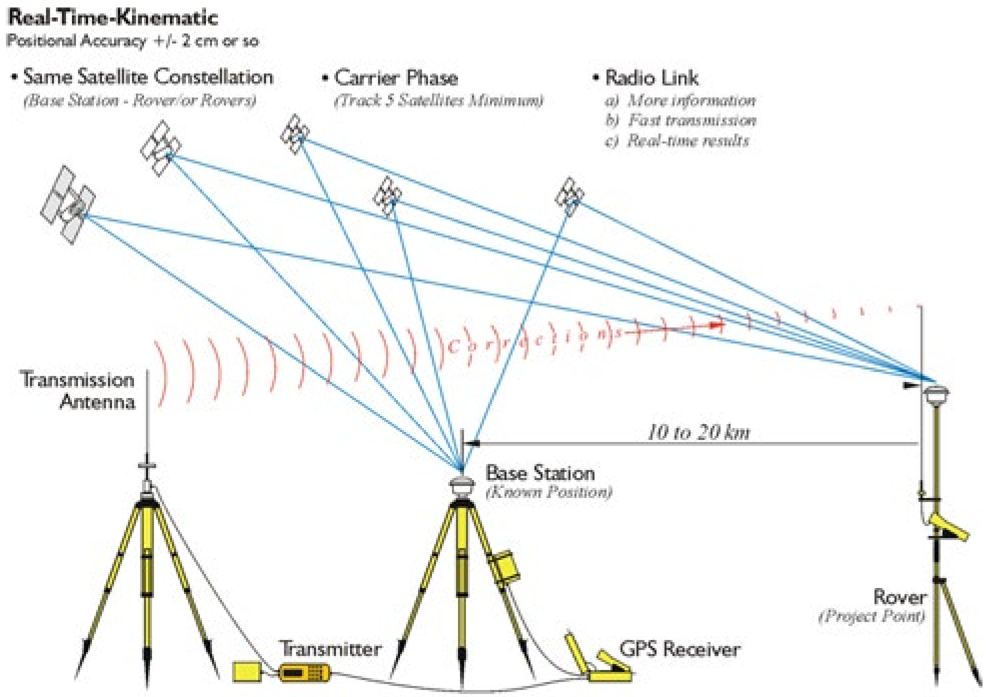
Fig. 5. Typical underwater camera and sonar images (approximately synchronized). The clear water and well-lit scenario represents some of the best possible optical conditions, nonetheless visibility is only a few meters. The 90° blazed array sonar horizontal image indicates three features (one at 5 m in front; one at 20 m and 5° to the left; and one at 35 m and 40° to the left), which is more than typical.

- **Advantages**:
  - Key sensor in underwater applications (SLAM)
  - Sonar can be used for underwater communication
  - Ultrasonic sensors are inexpensive & have low power consumption
- **Challenges**:
  - Limited range in air (vs Radar)
  - Susceptible to interference (ambient noise)
  - Sonar communication has very low bandwidth

GPS/GNSS



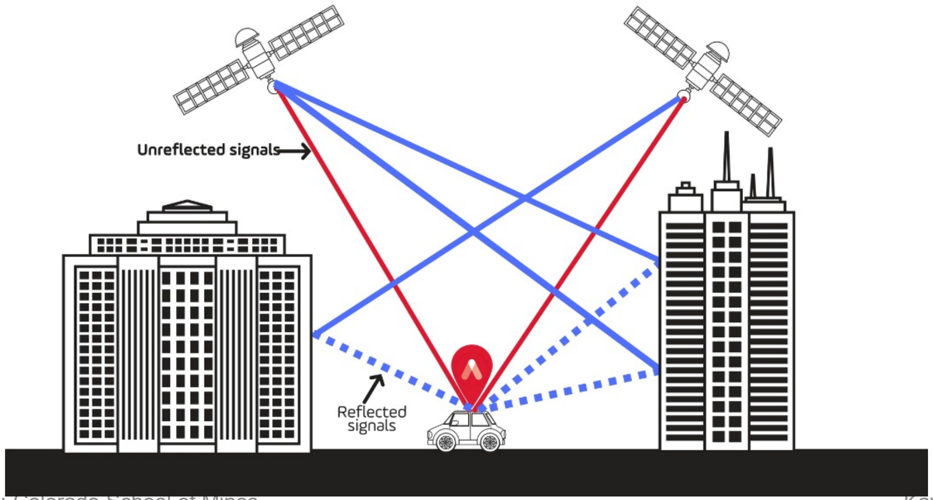


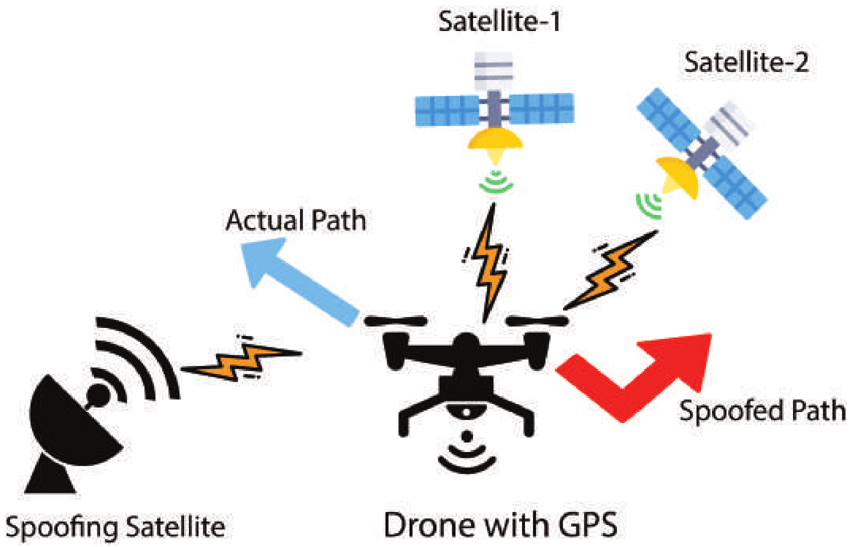


- **GPS** (Global Positioning System) is a satellite-based positioning system
- Each satellite continuously broadcasts signals with information about its position & and precise time
- Using the distance information (from at least 4 satellites), the GPS receiver performs “trilateration” to compute position in a global reference/earth frame
- **RTK** (real-time Kinematic) or **differential** GPS (DGPS) uses a base station (in addition to satellites) to improve accuracy (from meters to centimeters)

GPS/GNSS

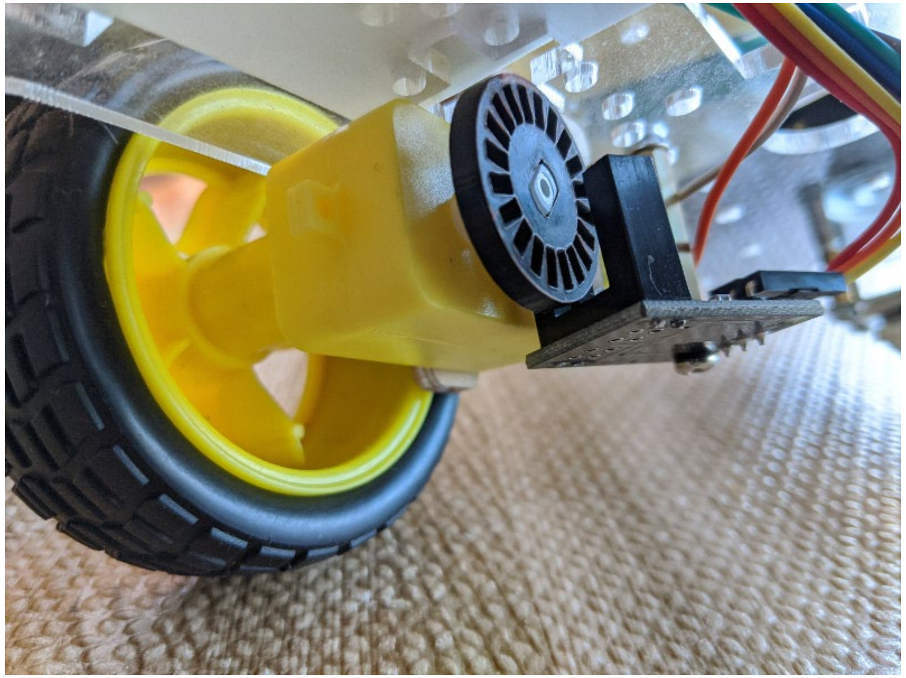
- **Advantages**:
  - Global coverage
  - Accurate centimeter-level positioning via RTK/DGPS
  - GPS can be used for time synchronization
- **Challenges**:
  - Unavailable indoor, underwater, subterranean, outer space. GPS signals are blocked by obstacles such as mountains, dense foliage, …
  - Reflections of GPS signals off surfaces (multipath interference) can create positioning errors (e.g., in downtowns with tall buildings)
  - GPS is vulnerable to spoofing (false signal injection) & jamming (interference)



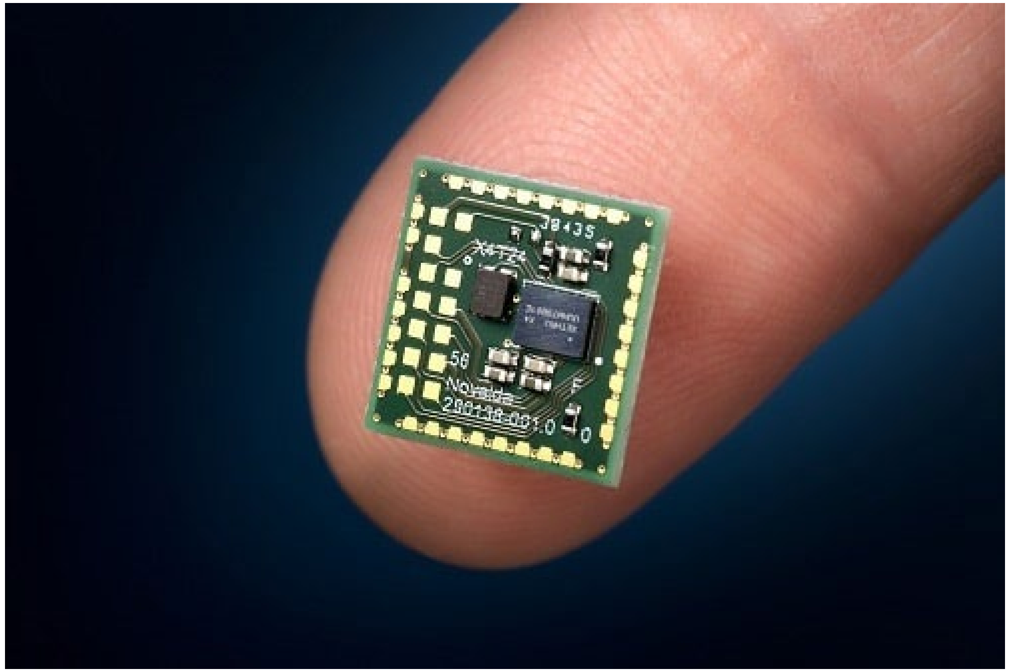


Other Sensors

- Various sensing technologies can be used for SLAM based on the application
- Examples:
  - **Encoders**: can be used to measure position, speed, or direction of motion
  - **Pressure sensors**: measure gas/liquid pressure, hence altitude/depth
  - **Ultra-Wideband** (**UWB**): use short-duration RF pulses (GHZ range) for communication and ranging (based on time of flight)



Wheel encoder

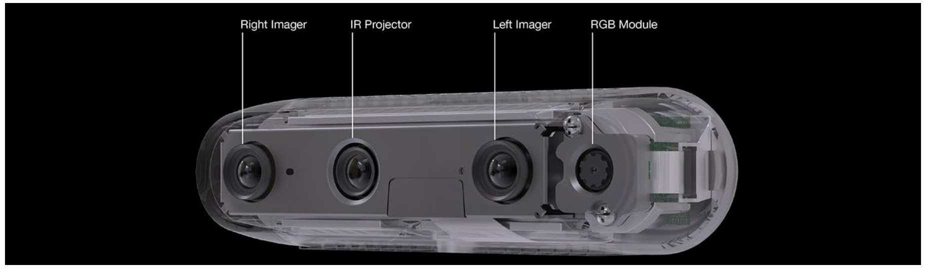


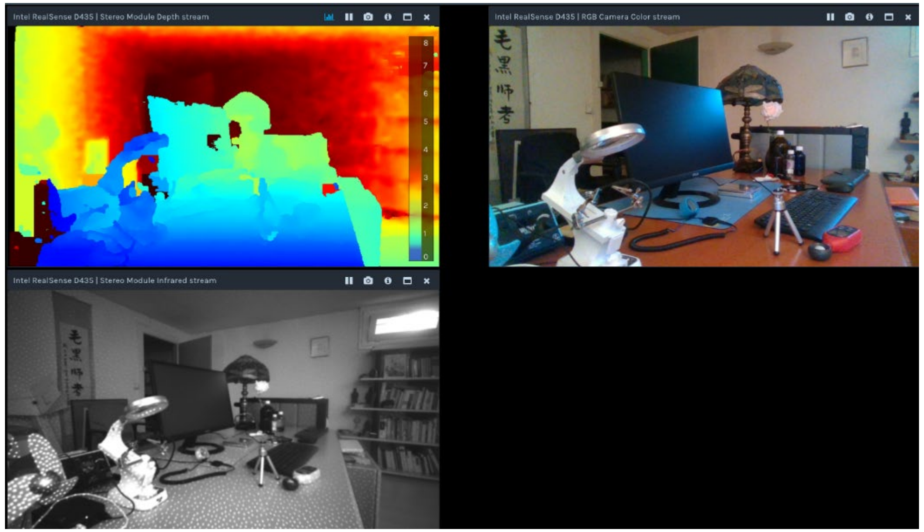
UWB sensor

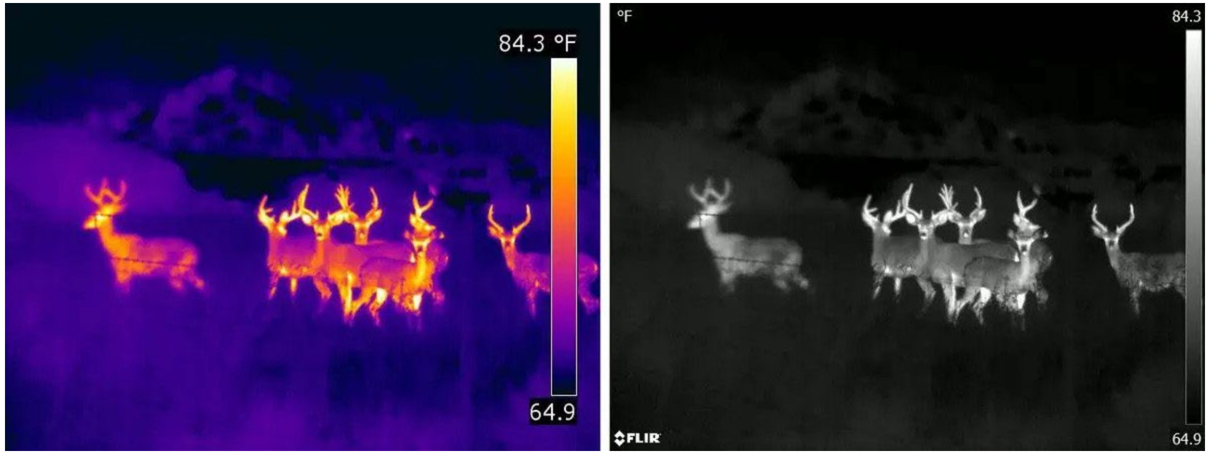

Time for
a BREAK

Sensors - Demo

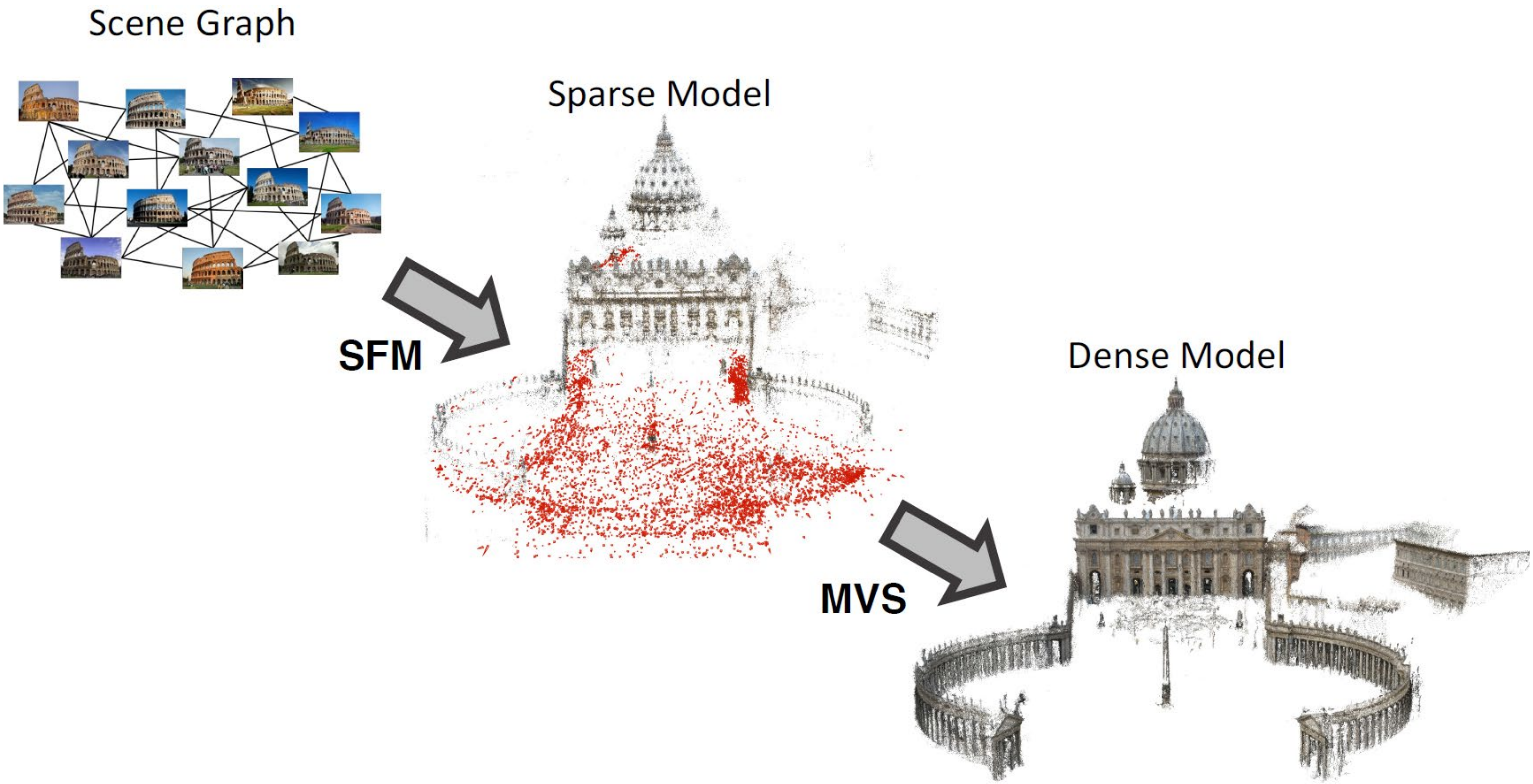
Intel RealSense D435







Structure from Motion (SfM)



SfM vs. SLAM: differences

SfM

- Input is **unordered** set of images
- Focus is on **precision**, with aim to produce a good 3D model
- **Offline**, one-time process
- Published mainly in **vision** conferences
- Complex

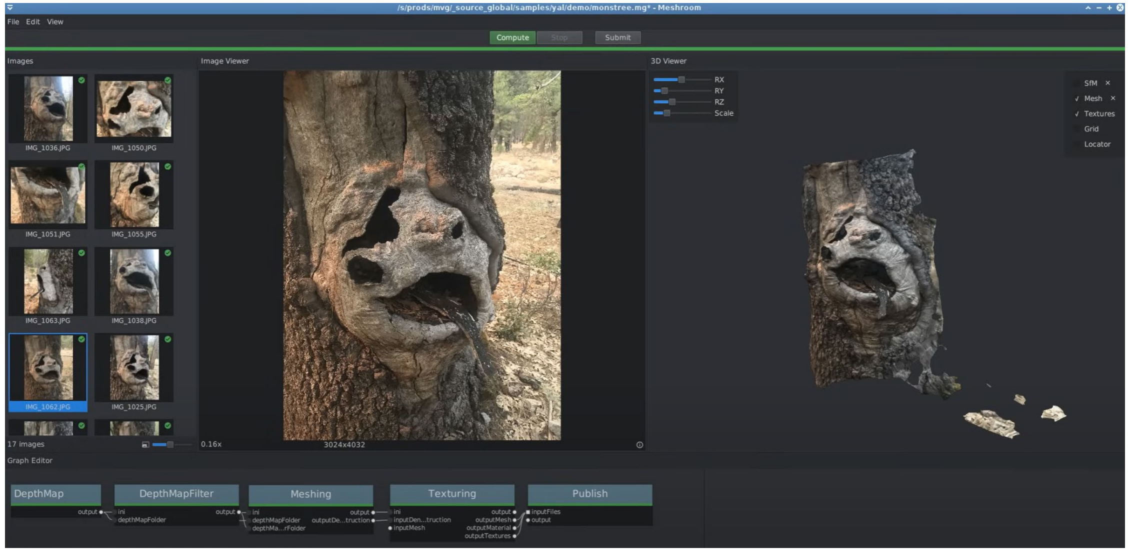
SLAM

- Input is **stream** of images, stereo, or depth and sometimes IMU
- Focus is on **speed** and robustness, with aim to localize camera or robot
- **Online** process, possibly with relocalization
- Published mainly in **robotics** conferences
- Very complex

SfM Demo

- Download & install Meshroom: https://alicevision.org/#meshroom

- Watch Meshroom tutorial: https://www.youtube.com/watch?v=v_O6tYKQEBA



- Download sample images: https://github.com/alicevision/dataset_monstree
- Create a 3D model using Meshroom (manual: https://meshroom-manual.readthedocs.io/en/latest/)