EECS 388: Embedded Systems

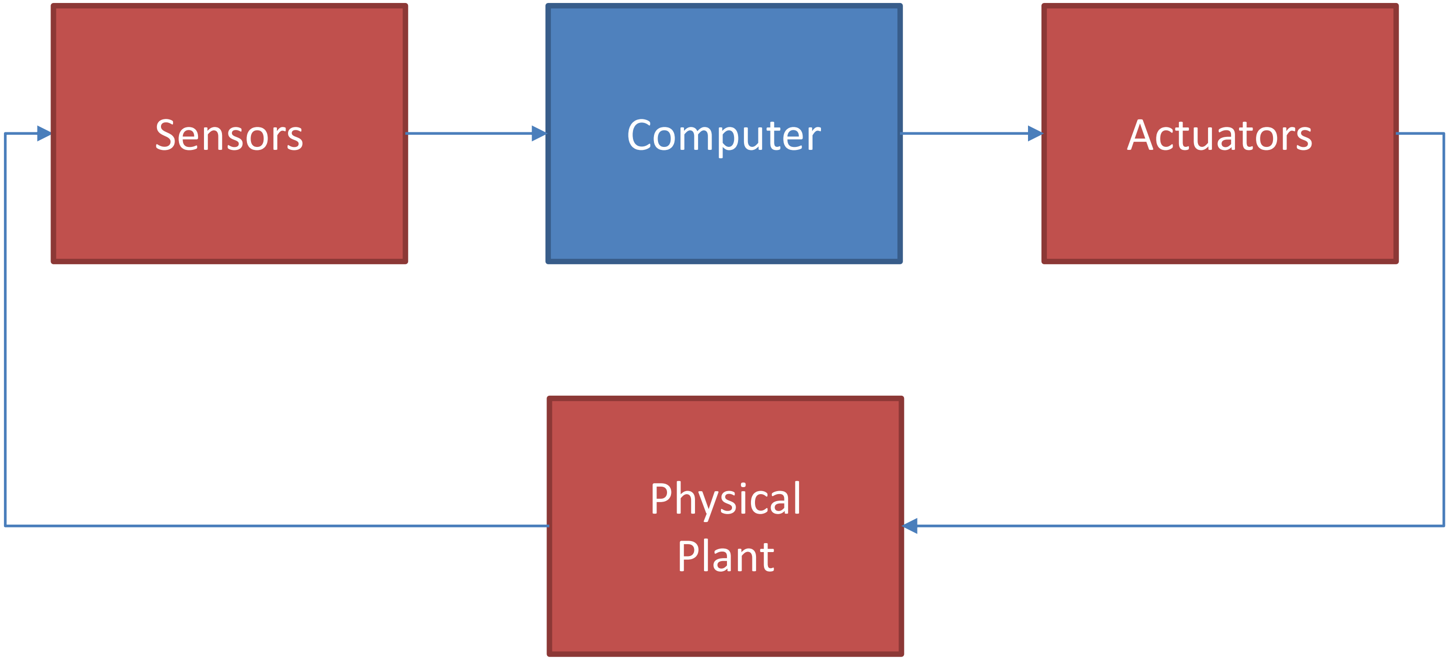
5. Sensors and Actuators

Heechul Yun

Agenda

- Sensors vs. actuators
  - Analog vs. digital
  - DAC, ADC
- Sensors
  - Accelerometers, gyro, magnetometer, GPS, radar, lidar, camera.
  - Nonlinearity, bias, dynamic range, quantization, noise, sampling, calibration
- Actuators
  - DC motors, PWM

Embedded/Cyber-Physical System



Sensors

Computer

Actuators

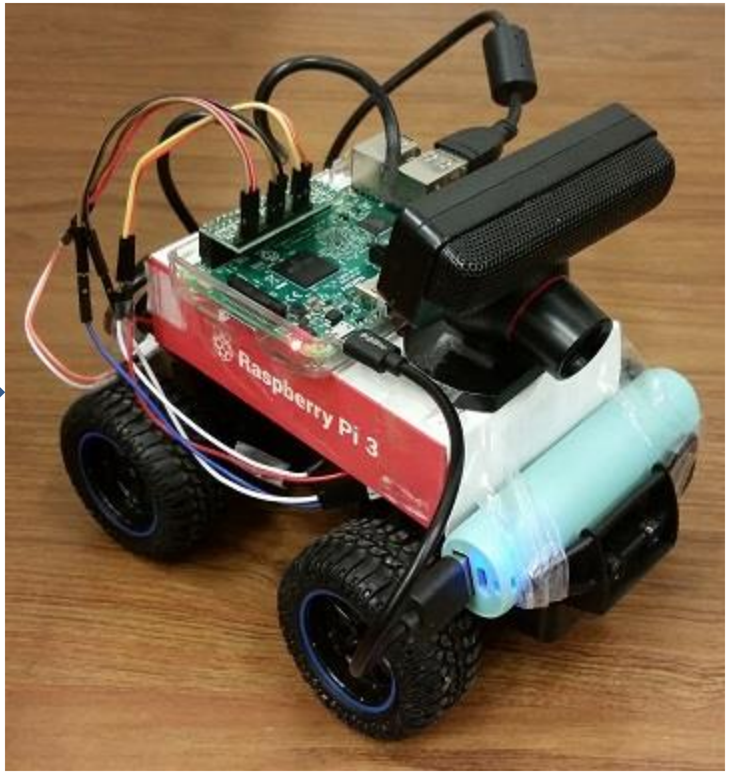
Physical Plant

Sensors and Actuators

DeepPicar

- Sensors and Actuators

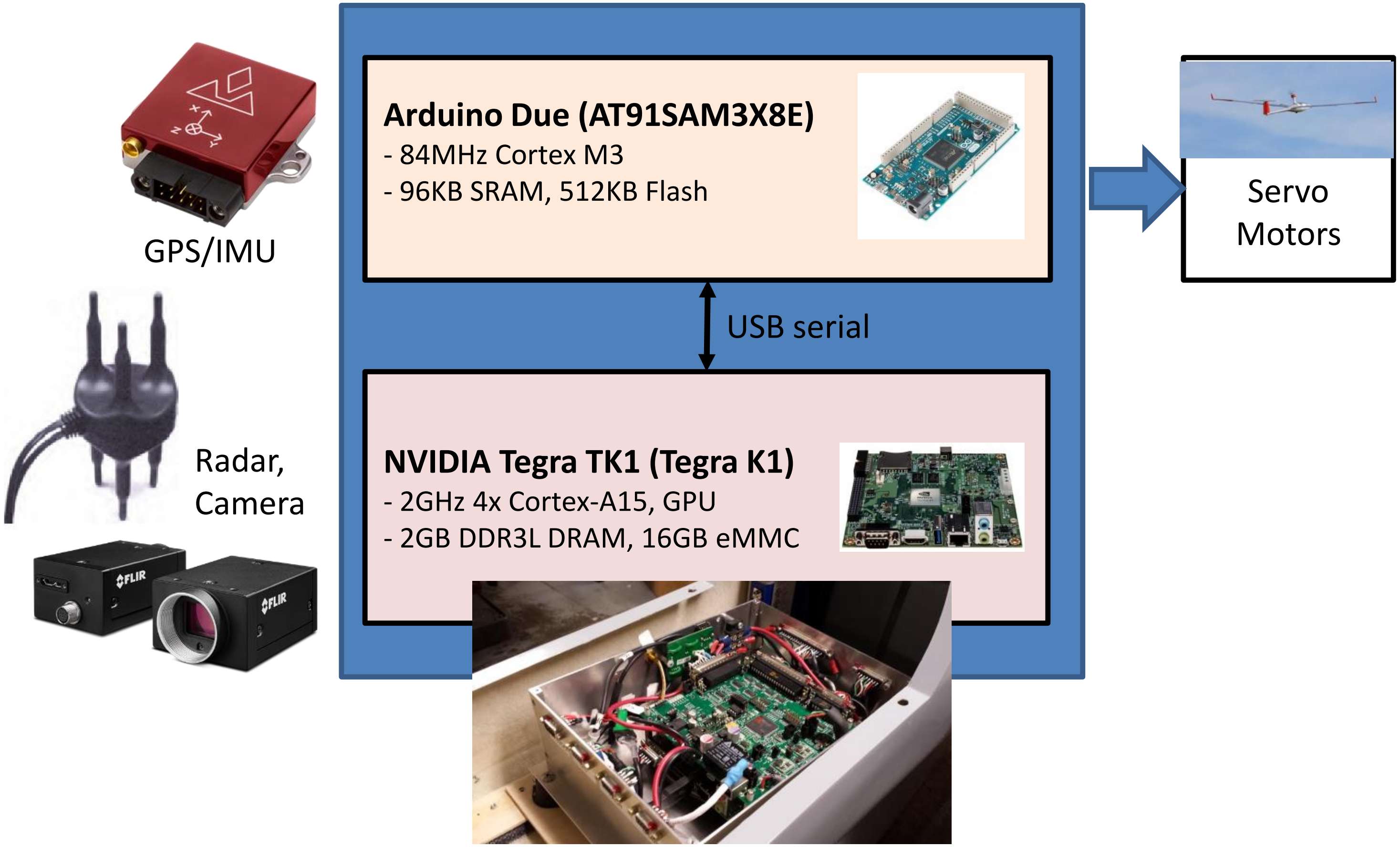
PlayStation Eye camera



DC Motors

KU AFS

- Sensors and Actuators



GPS/IMU

Radar,
Camera

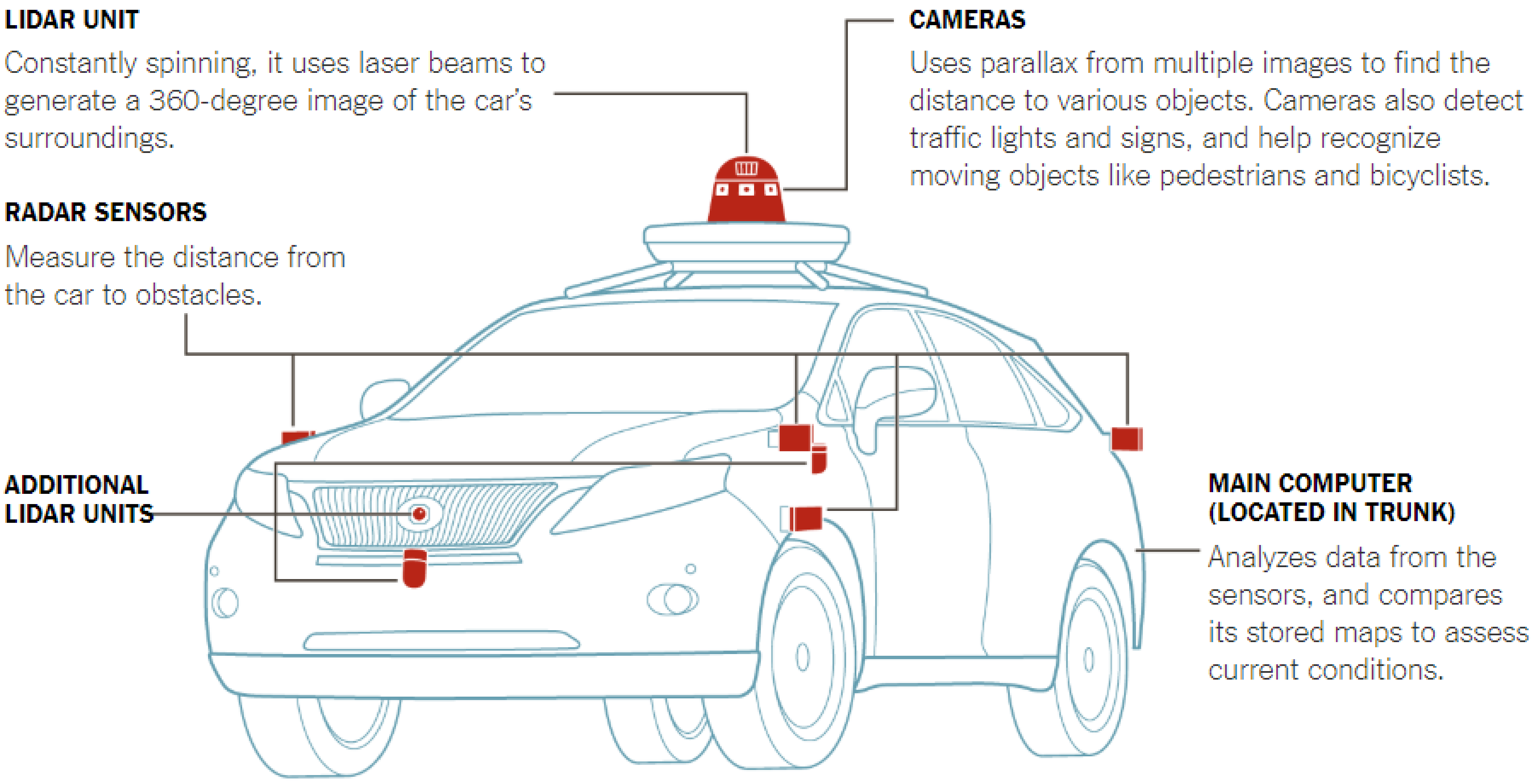
Arduino Due (AT91SAM3X8E)
- 84MHz Cortex M3
- 96KB SRAM, 512KB Flash

USB serial

NVIDIA Tegra TK1 (Tegra K1)
- 2GHz 4x Cortex-A15, GPU
- 2GB DDR3L DRAM, 16GB eMMC

Servo
Motors

Google Self-Driving Car Sensors



LIDAR UNIT

Constantly spinning, it uses laser beams to generate a 360-degree image of the car's surroundings.

CAMERAS

Uses parallax from multiple images to find the distance to various objects. Cameras also detect traffic lights and signs, and help recognize moving objects like pedestrians and bicyclists.

RADAR SENSORS

Measure the distance from the car to obstacles.

ADDITIONAL LIDAR UNITS

MAIN COMPUTER (LOCATED IN TRUNK)

Analyzes data from the sensors, and compares its stored maps to assess current conditions.

By Guilbert Gates | Source: Google | Note: Car is a Lexus model modified by Google.

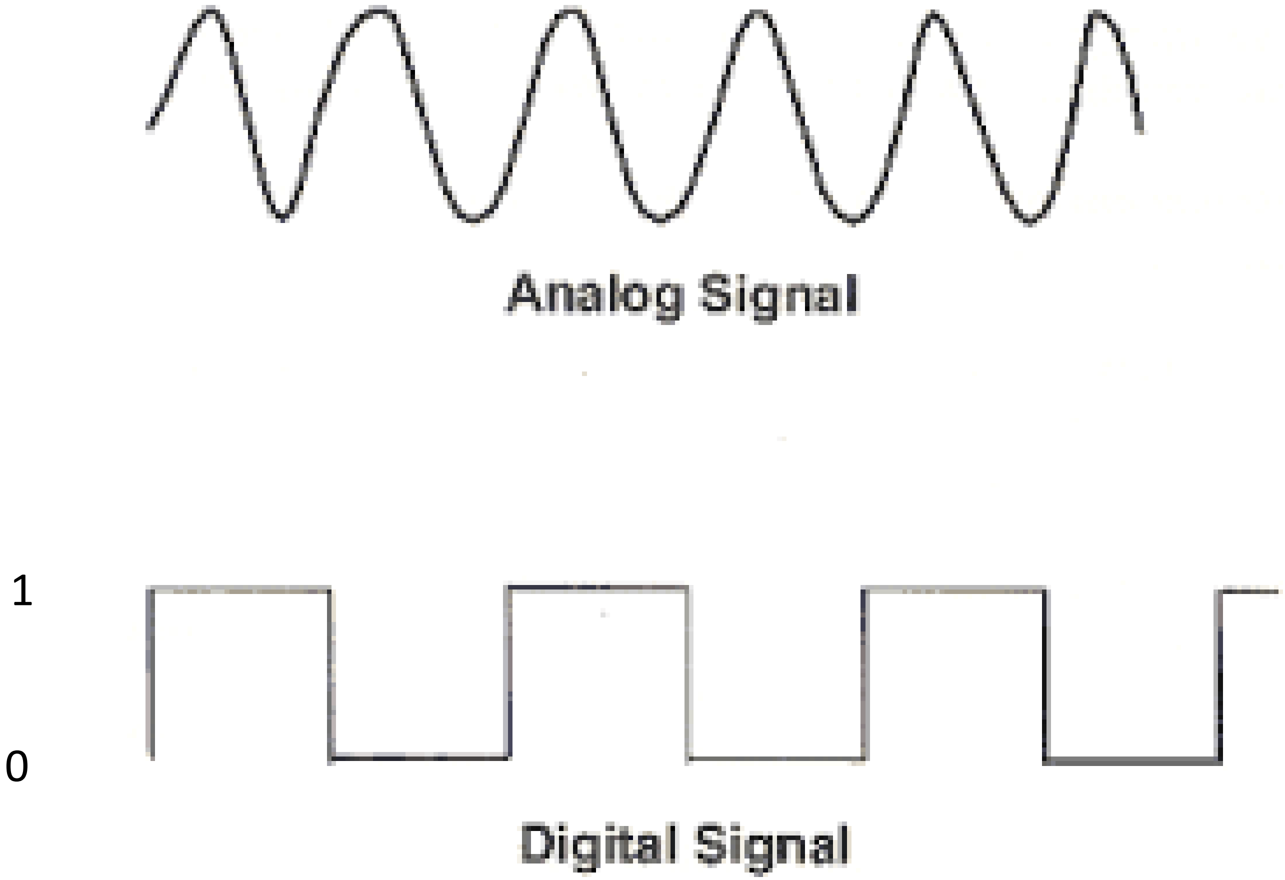
https://www.nytimes.com/interactive/2016/12/14/technology/how-self-driving-cars-work.html

Sensors and Actuators

- Sensor
  - Measure a physical quantity
  - Input: “Read from physical world”

- Actuator
  - Alter a physical quantity
  - Output: “Write to physical world”

Digital vs. Analog Signals



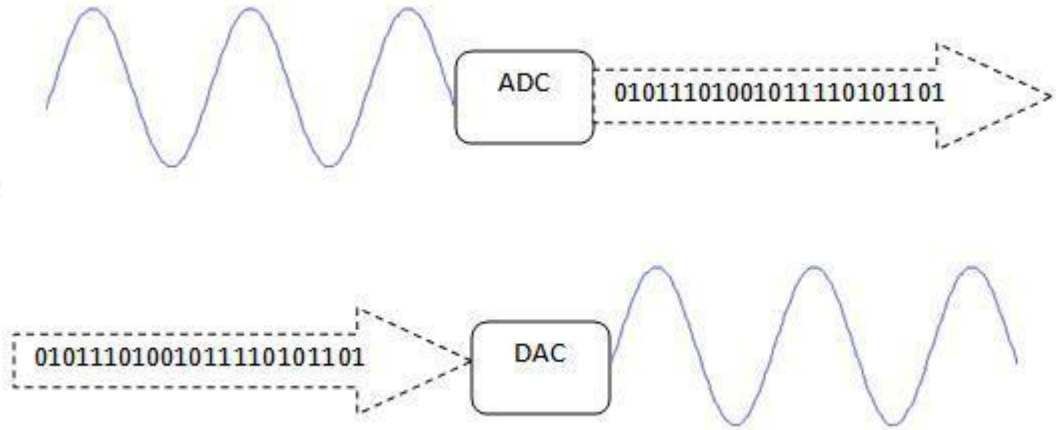
Physical world

Cyber world

This Photo by Unknown Author is licensed under CC BY-SA

ADC and DAC

- ADC (analog-to-digital converter)
  - Convert an analog signal into a digital one
- DAC (digital-to-analog converter)
  - Convert a digital signal into an analog one



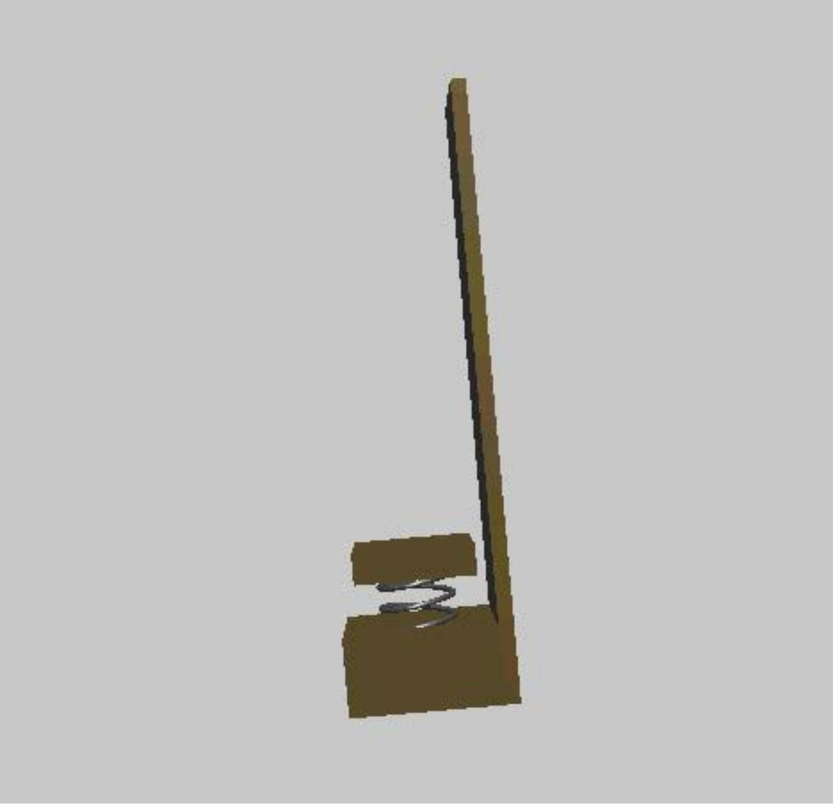
Sensors

- Accelerometer
- Gyro
- Magnetometer
- GPS
- Ultrasonic
- Lidar
- Radar
- Camera

Accelerometer

- Measure acceleration
  - F = ma
  - Earth's gravitational force is balanced by the restoring force of the spring

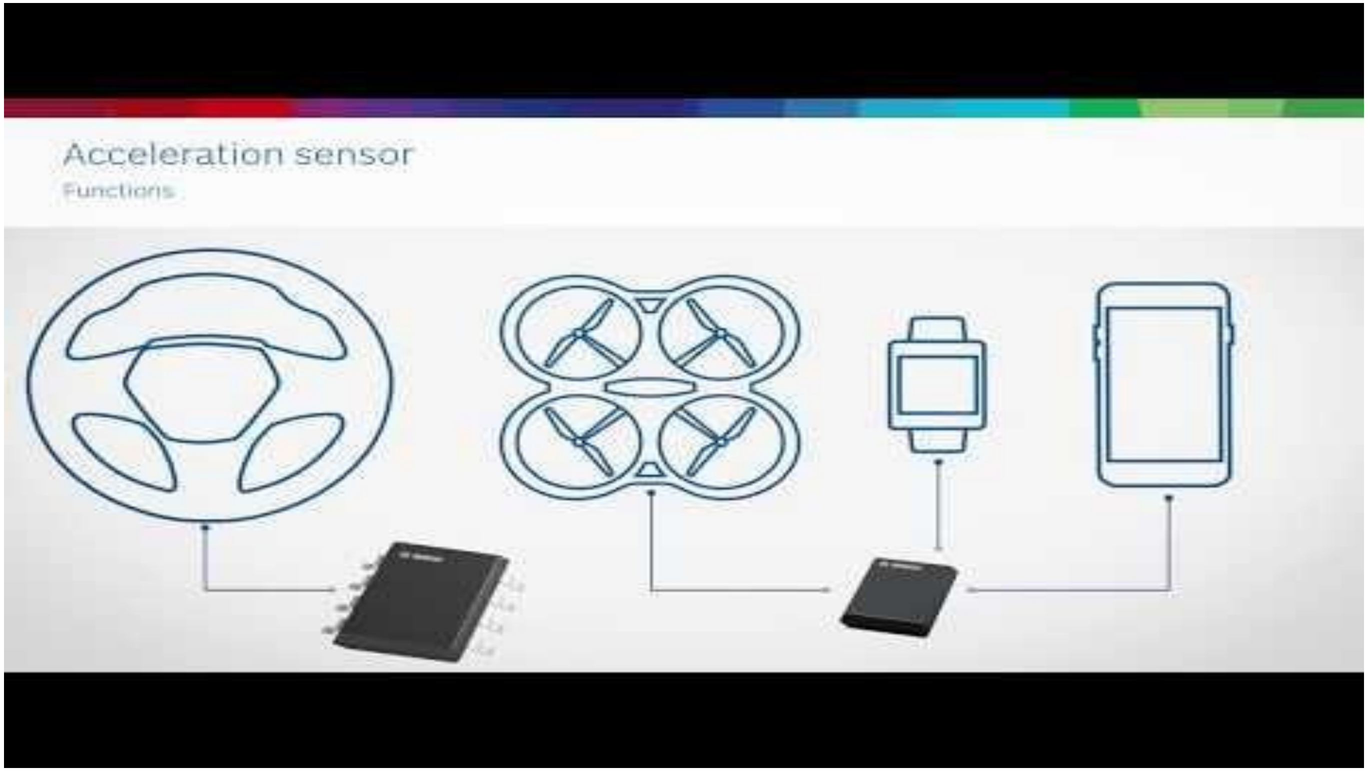
Spring-Mass-Damper model



Source: E. A Lee, UCB

MEMS Accelerometer

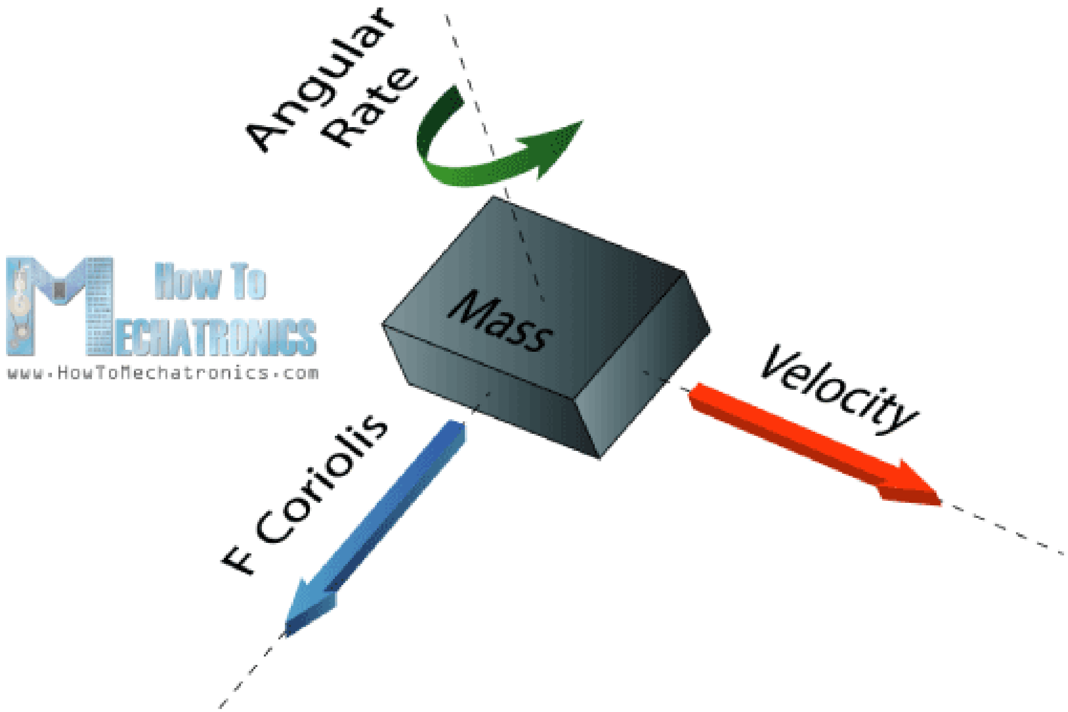
- Micro-electro mechanical systems (MEMS)
  - Very small mechanical structure (moving parts)



https://www.youtube.com/watch?v=RLQGZl0lpjQ

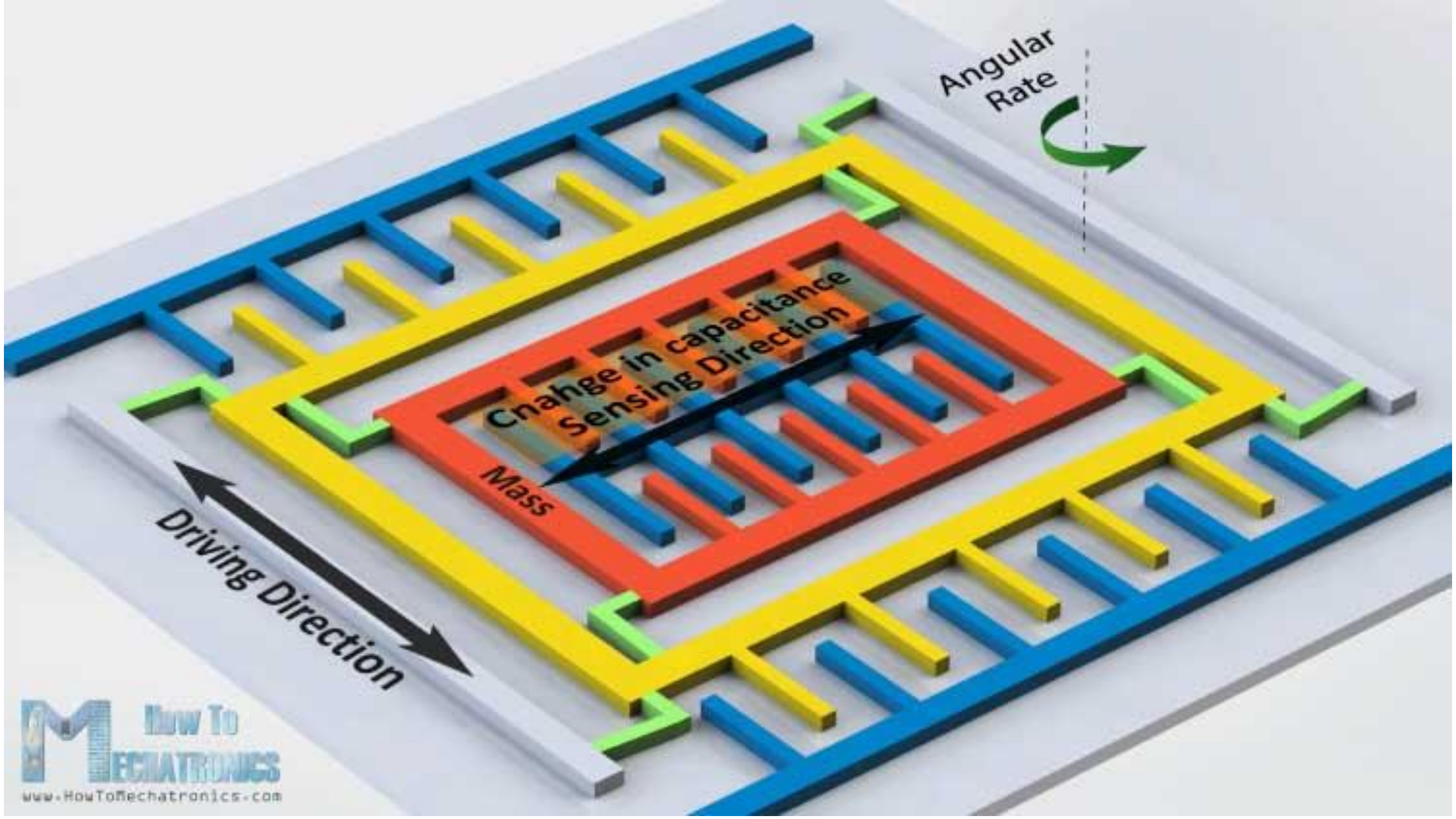
Gyroscope

- Measure angular velocity
  - Coriolis force



https://howtomechatronics.com/how-it-works/electrical-engineering/mems-accelerometer-gyrocope-magnetometer-arduino/

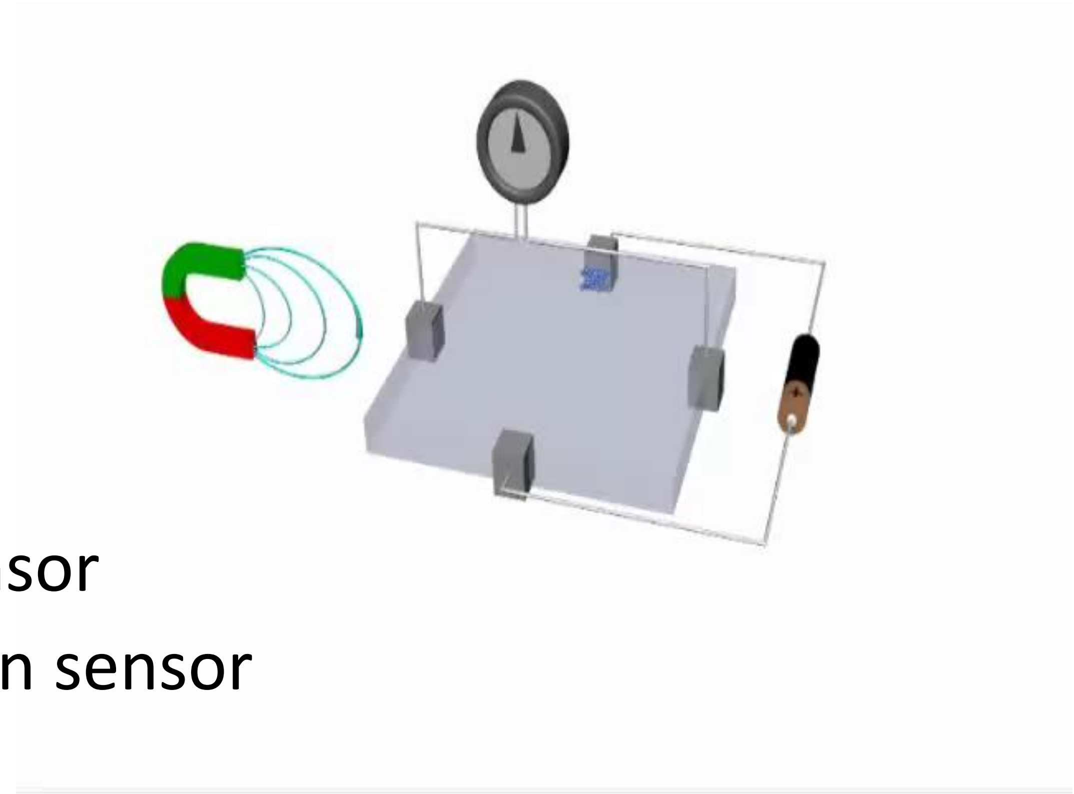
MEMS Gyroscope



https://howtomechatronics.com/how-it-works/electrical-engineering/mems-accelerometer-gyrocope-magnetometer-arduino/

Magnetometer

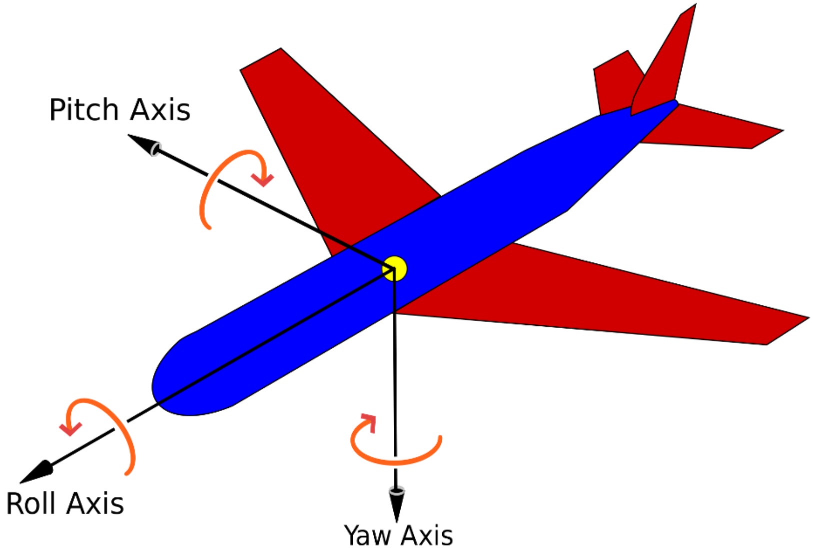
- Measure magnetic field
  - Hall effect
- Use cases
  - Compass
  - Proximity sensor
  - Wheel speed sensor
  - Camshaft position sensor
  - …



https://en.wikipedia.org/wiki/File:Hall_Sensor.webm

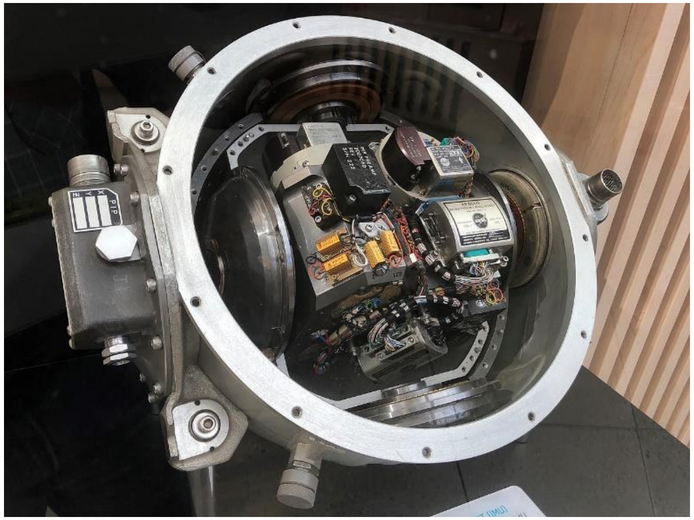
Inertial Measurement Unit (IMU)

- Accelerometer + gyroscope + (magnetometer)
- Use cases: Maneuver UAV, satellite, etc.



Roll, Yaw, Pitch

https://en.wikipedia.org/wiki/Flight_dynamics_(fixed-wing_aircraft)

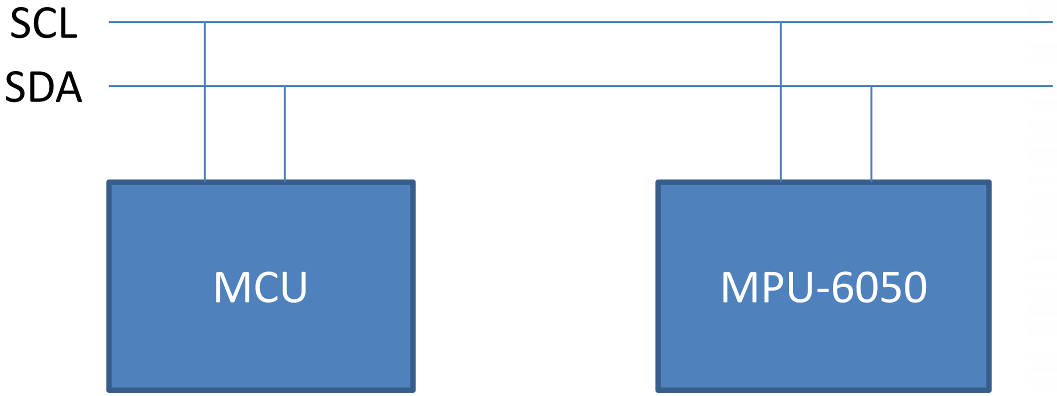


Apollo Inertial Measurement Unit

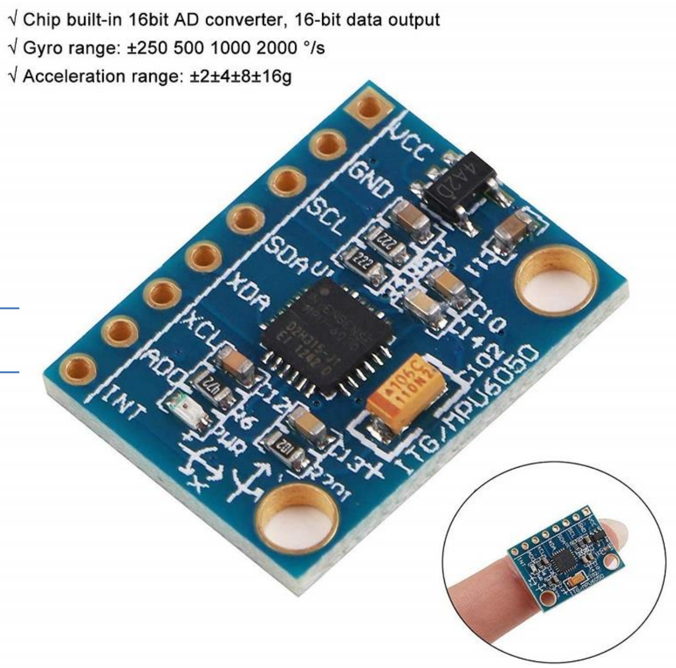
https://en.wikipedia.org/wiki/Inertial_measurement_unit

MPU-6050

- 3-axis gyroscopes, 3-axis accelerometers
- A single chip MEMS sensors
- I^{2}C interface
- 16 bit ADC

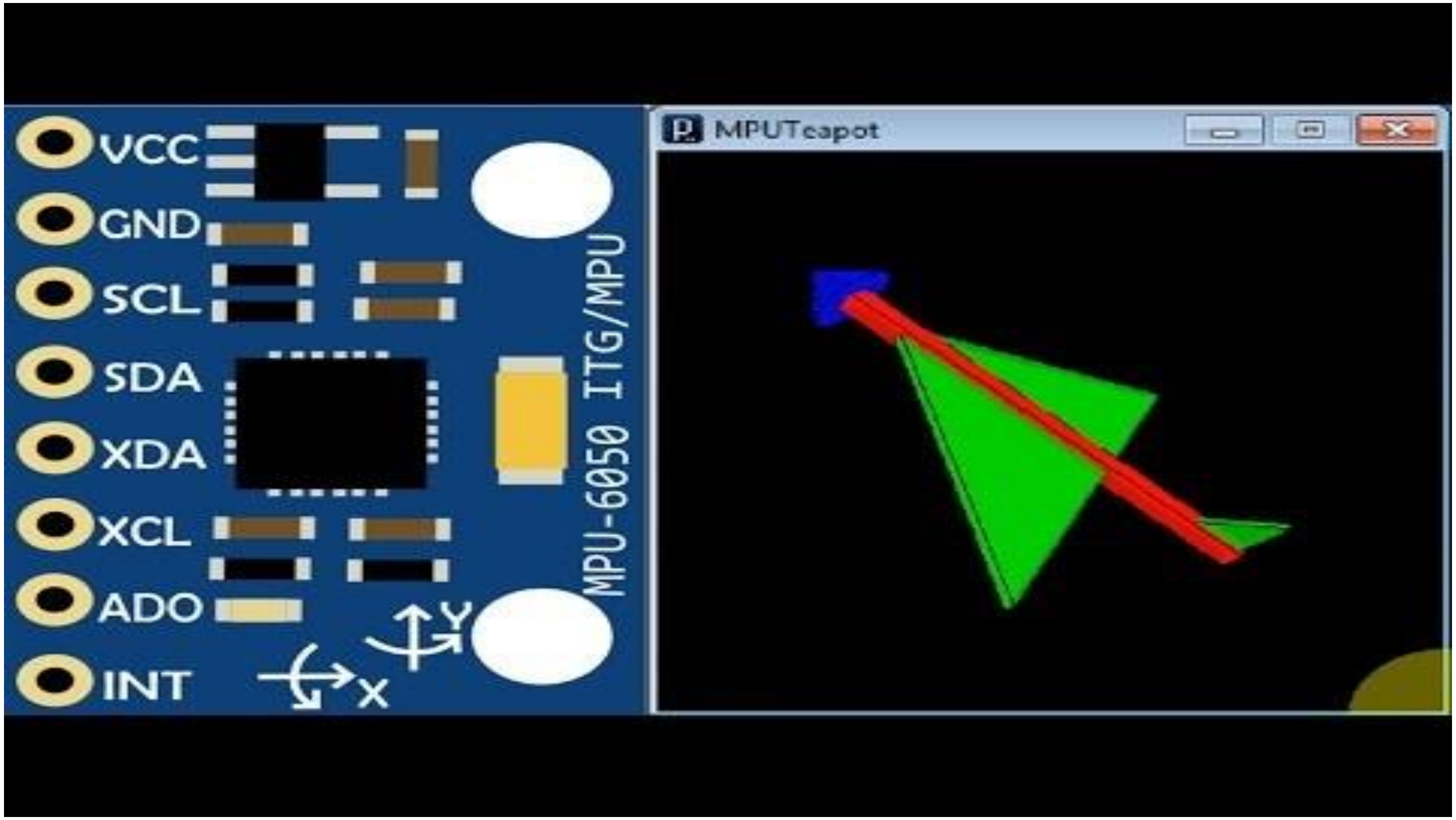


0b1101000



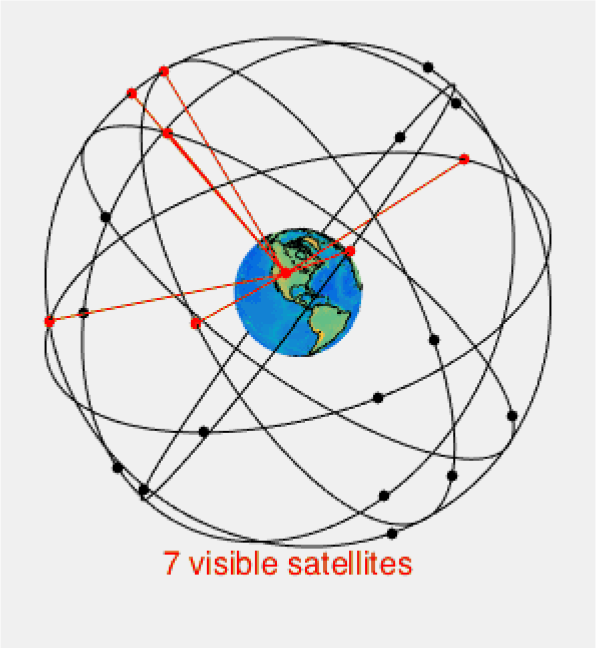
√ Chip built-in 16bit AD converter, 16-bit data output
√ Gyro range: ±250 500 1000 2000 °/s
√ Acceleration range: ±2±4±8±16g

MPU-6050



GPS

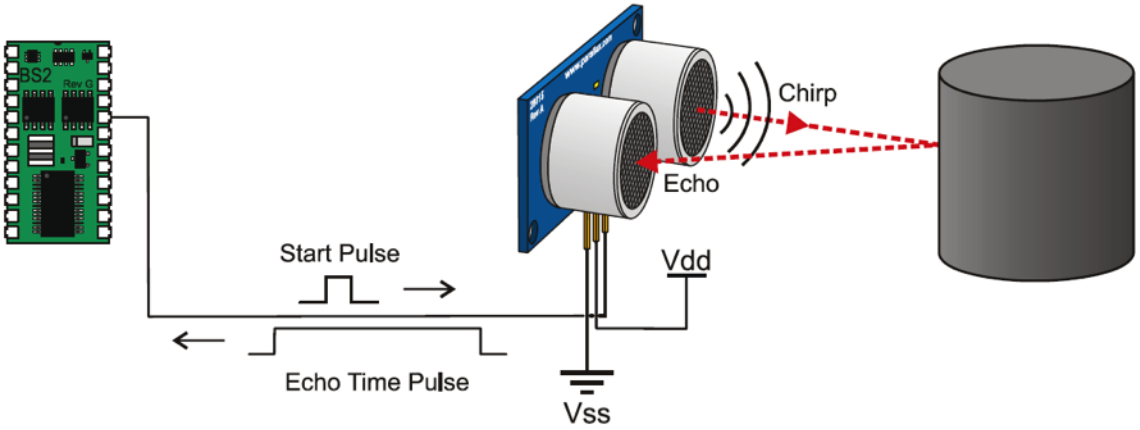
- Global positioning system: a satellite based system owned and operated by US gov.
- Fundamental
  - Radio signals from satellites moves at a constant speed
  - The time difference is proportional to the distance
  - With at least four satellites, location can be determined
  - 50 bit/s, takes 30-40 sec, 5-10 meter position errors



By Paulsava, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=47210072

Ultrasonic

- Use sound waves to detect objects
- Cheap, works well in bad weather
- Short range



https://electronics.stackexchange.com/questions/177897/what-sensors-shall-be-used-to-detect-if-a-dustbin-is-full-light-weight-material

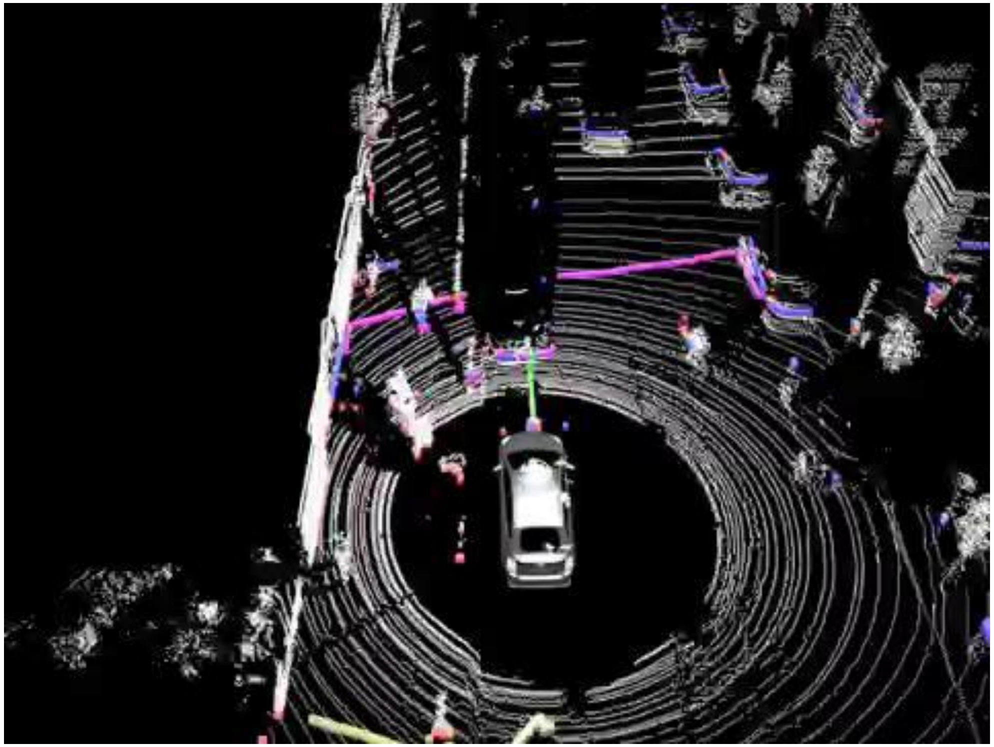
Radar

- Use radio waves to detect objects
- Does well in bad weather
- Low resolution

[Self-Driving Cars State of the Art (2019)](https://deeplearning.mit.edu), https://deeplearning.mit.edu

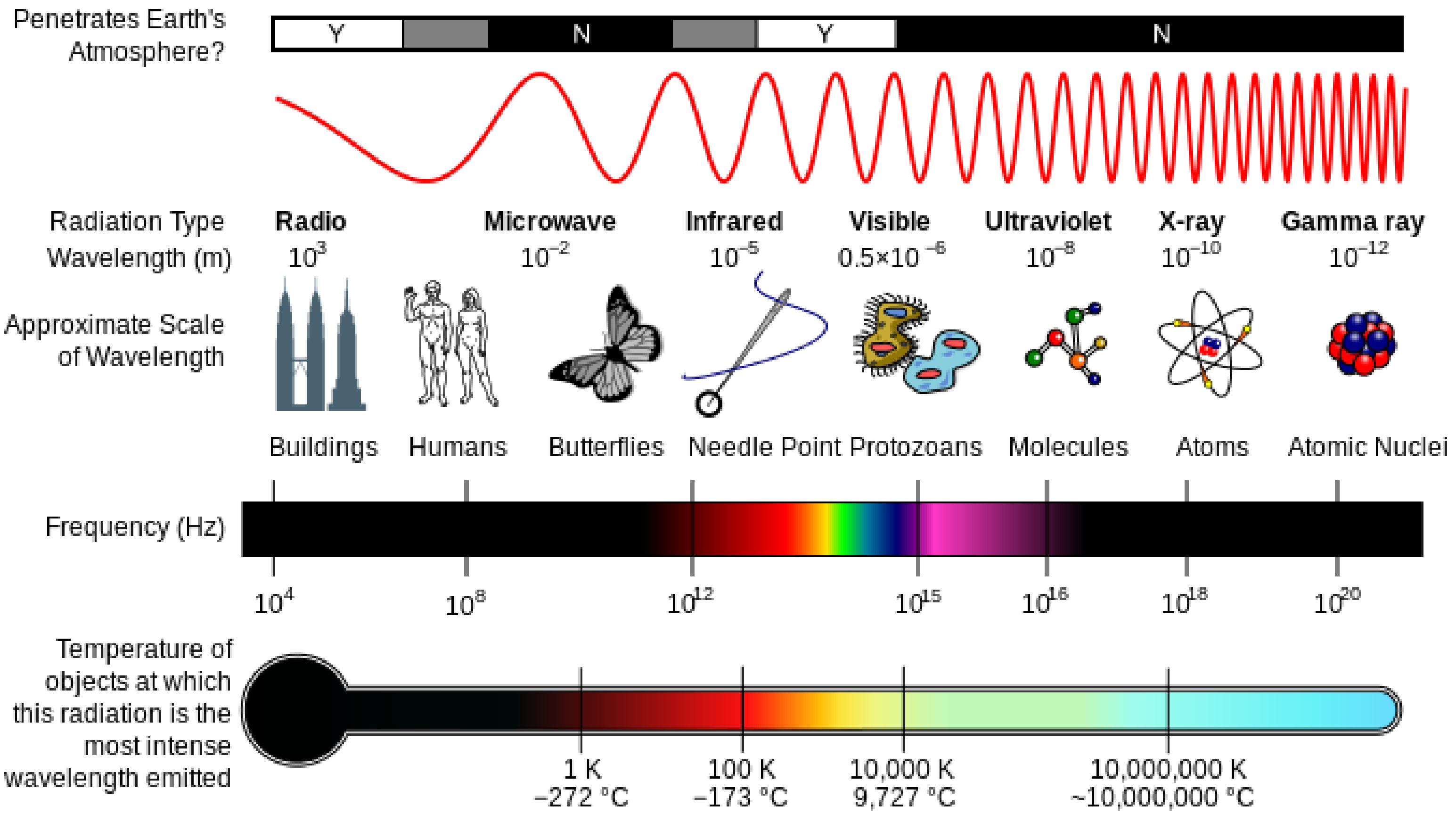
Lidar

- Use light (laser) to detect objects
- Very accurate 360 degree depth information
- Used by most self-driving cars
- Expensive



[Self-Driving Cars State of the Art (2019)](https://deeplearning.mit.edu), https://deeplearning.mit.edu

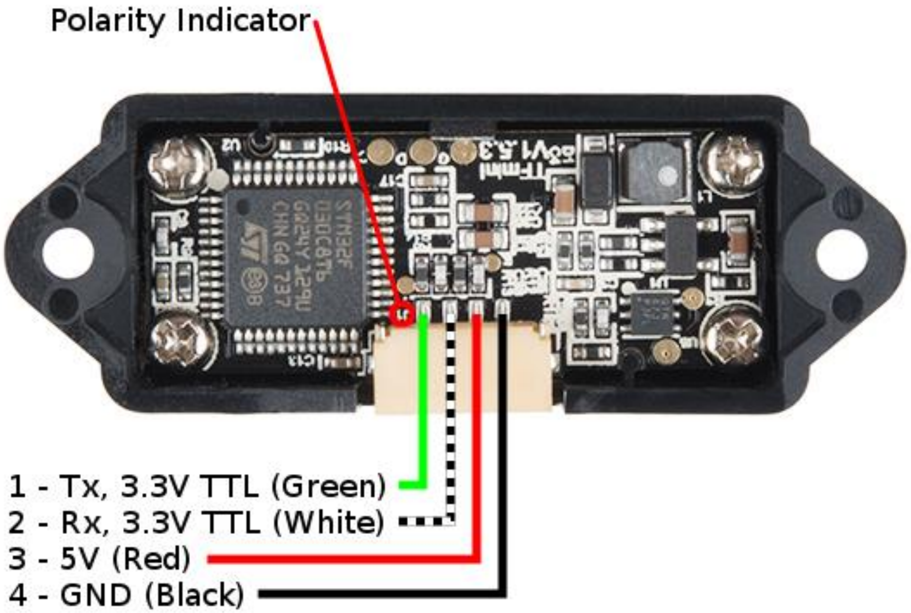
Electromagnetic Waves:
Radio (Radar) vs. Light (Lidar)



https://en.wikipedia.org/wiki/Electromagnetic_spectrum#/media/File:EM_Spectrum_Properties_edit.svg

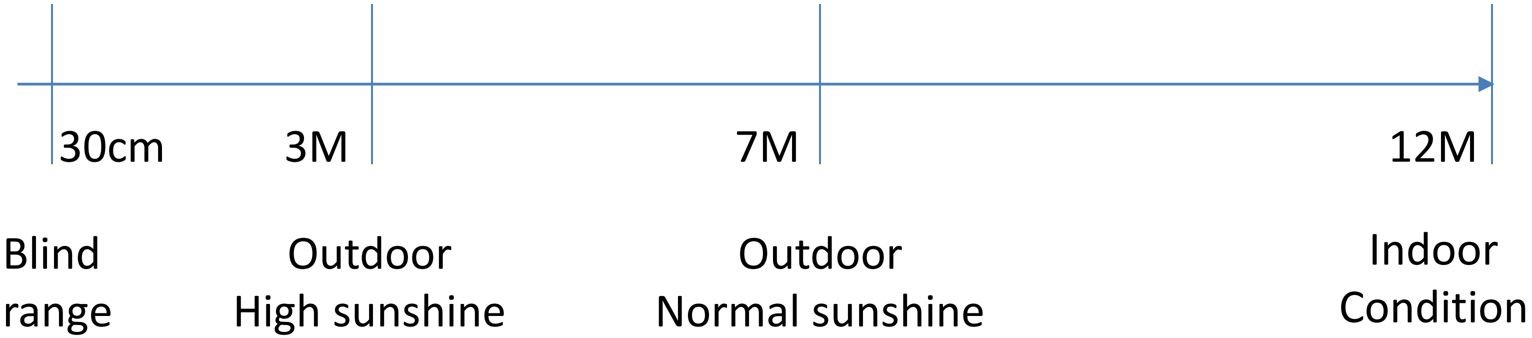
TFMini Lidar

- Use LED (instead of laser) to detect objects
- Single direction (single point estimate)
- UART interface



TFMini Lidar

- Detection range



30cm 3M 7M 12M

Blind range

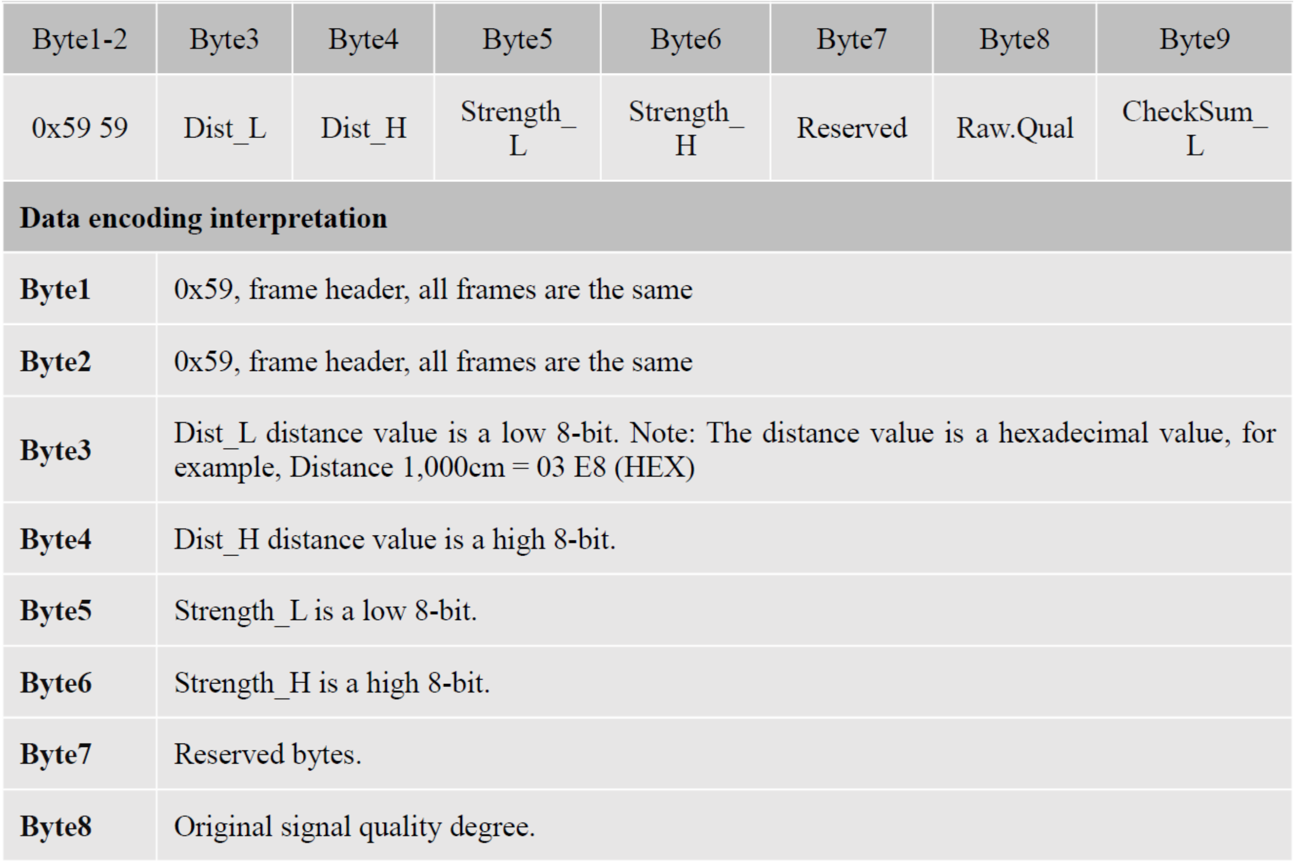
Outdoor
High sunshine

Outdoor
Normal sunshine

Indoor
Condition

TFMini Lidar

- Data format



Byte1-2	Byte3	Byte4	Byte5	Byte6	Byte7	Byte8	Byte9
0x59 59	Dist_L	Dist_H	Strength_ L	Strength_ H	Reserved	Raw.Qual	CheckSum_ L

Data encoding interpretation	
Byte1	0x59, frame header, all frames are the same
Byte2	0x59, frame header, all frames are the same
Byte3	Dist_L distance value is a low 8-bit. Note: The distance value is a hexadecimal value, for example, Distance 1,000cm = 03 E8 (HEX)
Byte4	Dist_H distance value is a high 8-bit.
Byte5	Strength_L is a low 8-bit.
Byte6	Strength_H is a high 8-bit.
Byte7	Reserved bytes.
Byte8	Original signal quality degree.

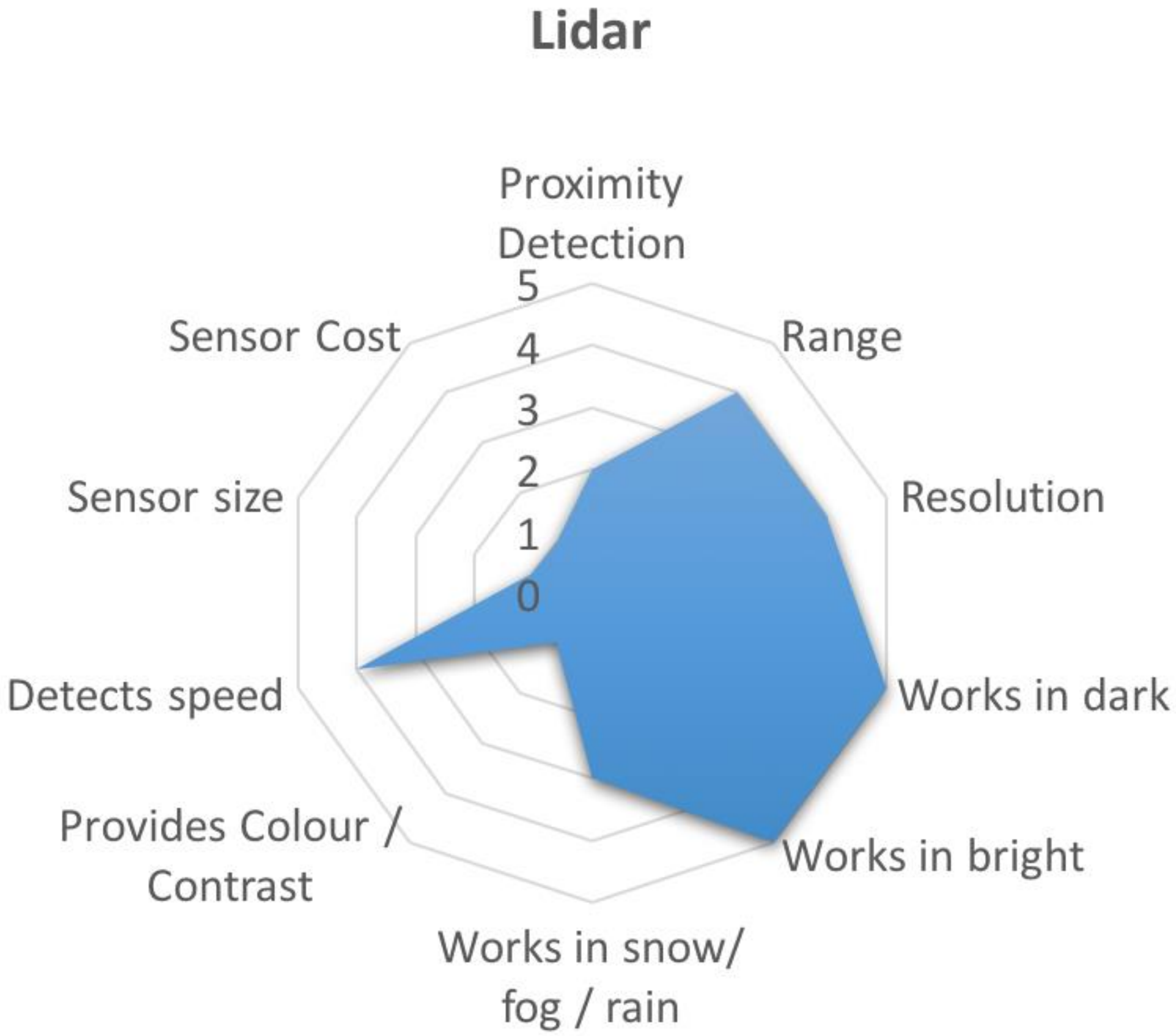
Camera

- Inexpensive, highest resolution
- Require high computing capacity
- Not good in bad weathers, at depth estimation

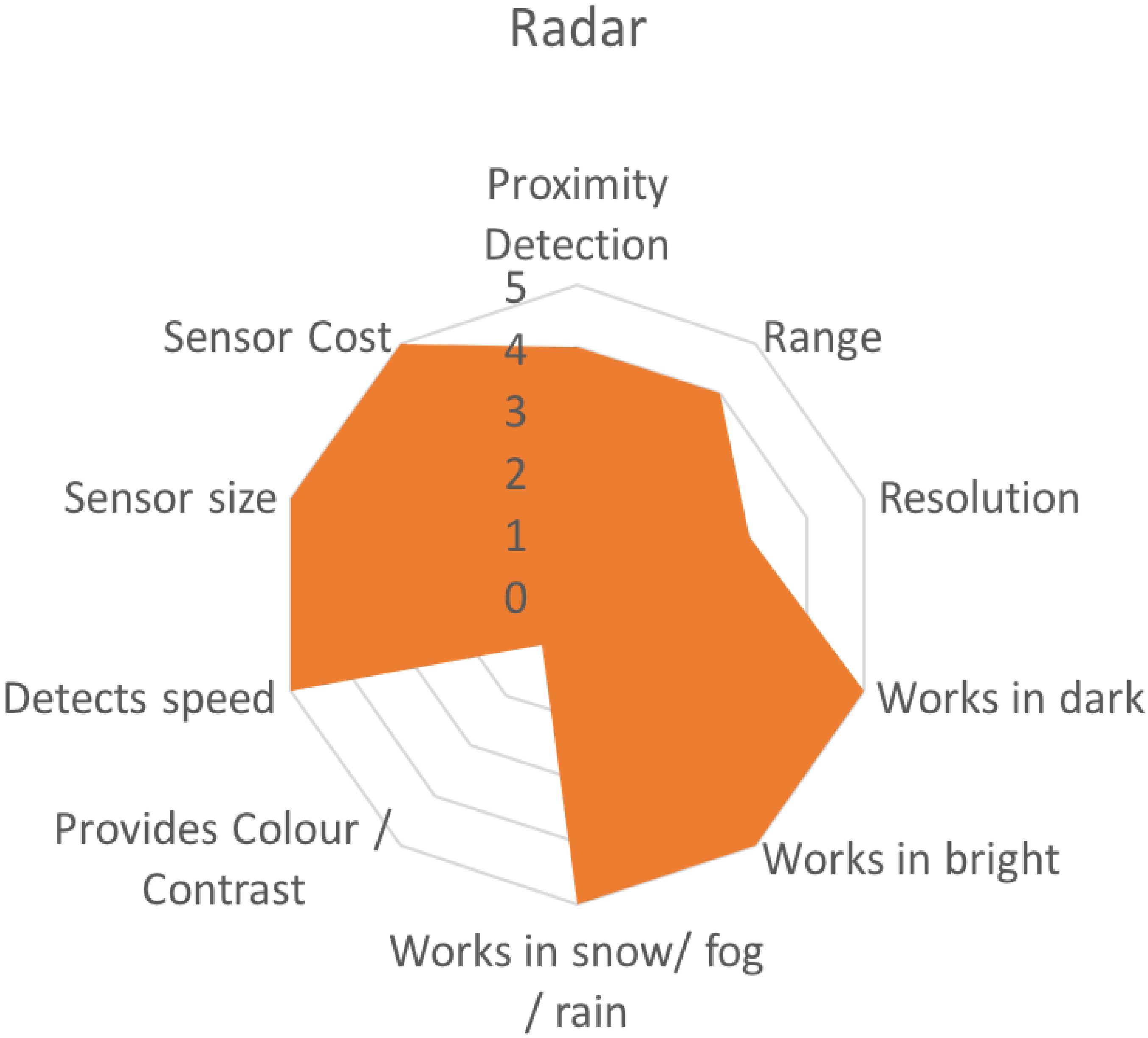
Self-Driving Cars State of the Art (2019), https://deeplearning.mit.edu

Recap

- Digital vs. Analog
- ADC vs. DAC
- Accelerometer, Gyro, Magnetometer, IMU
- Ultrasonic, Lidar, Laser, Camera

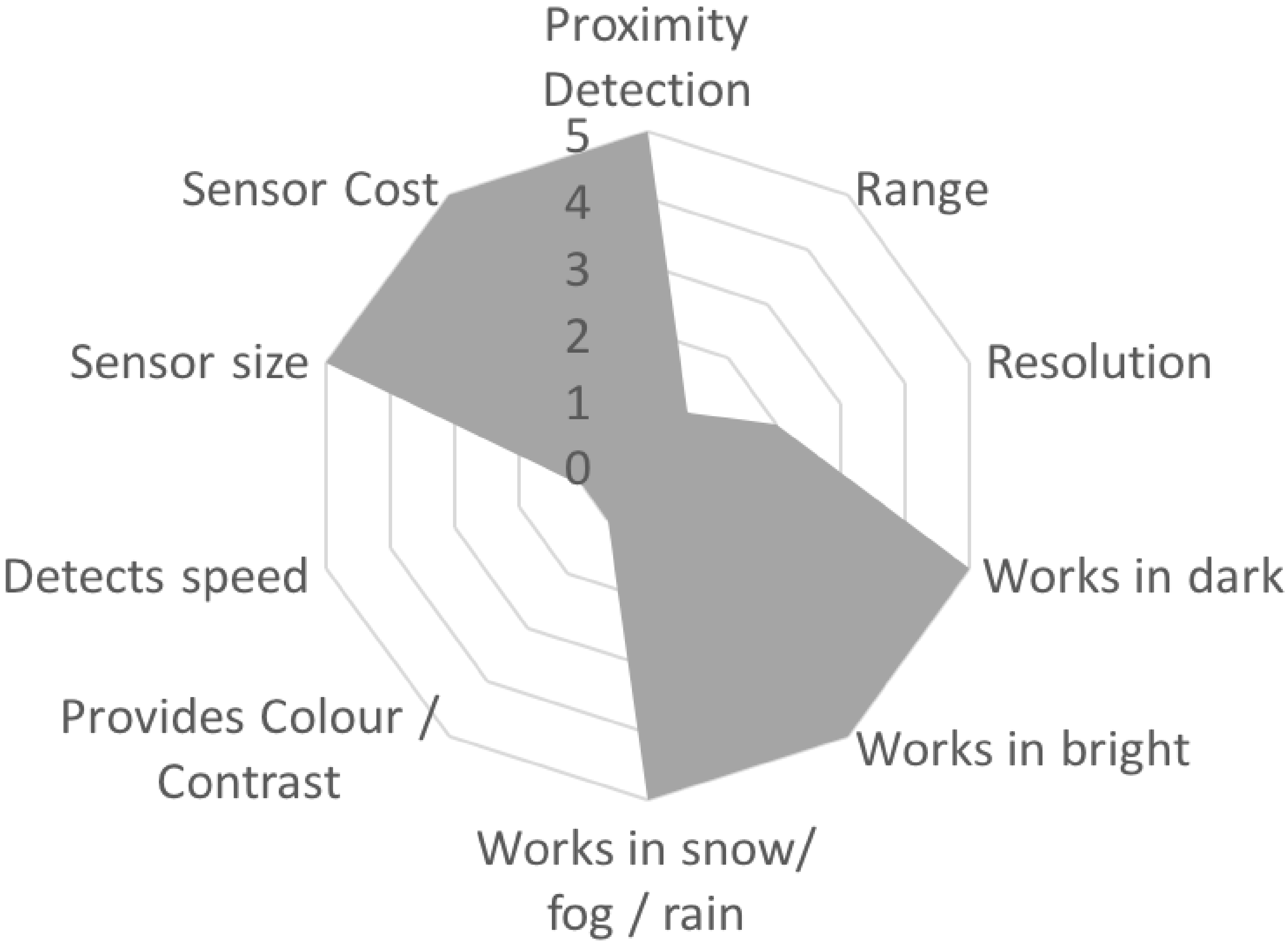


https://cleantechnica.com/2016/07/29/tesla-google-disagree-lidar-right/



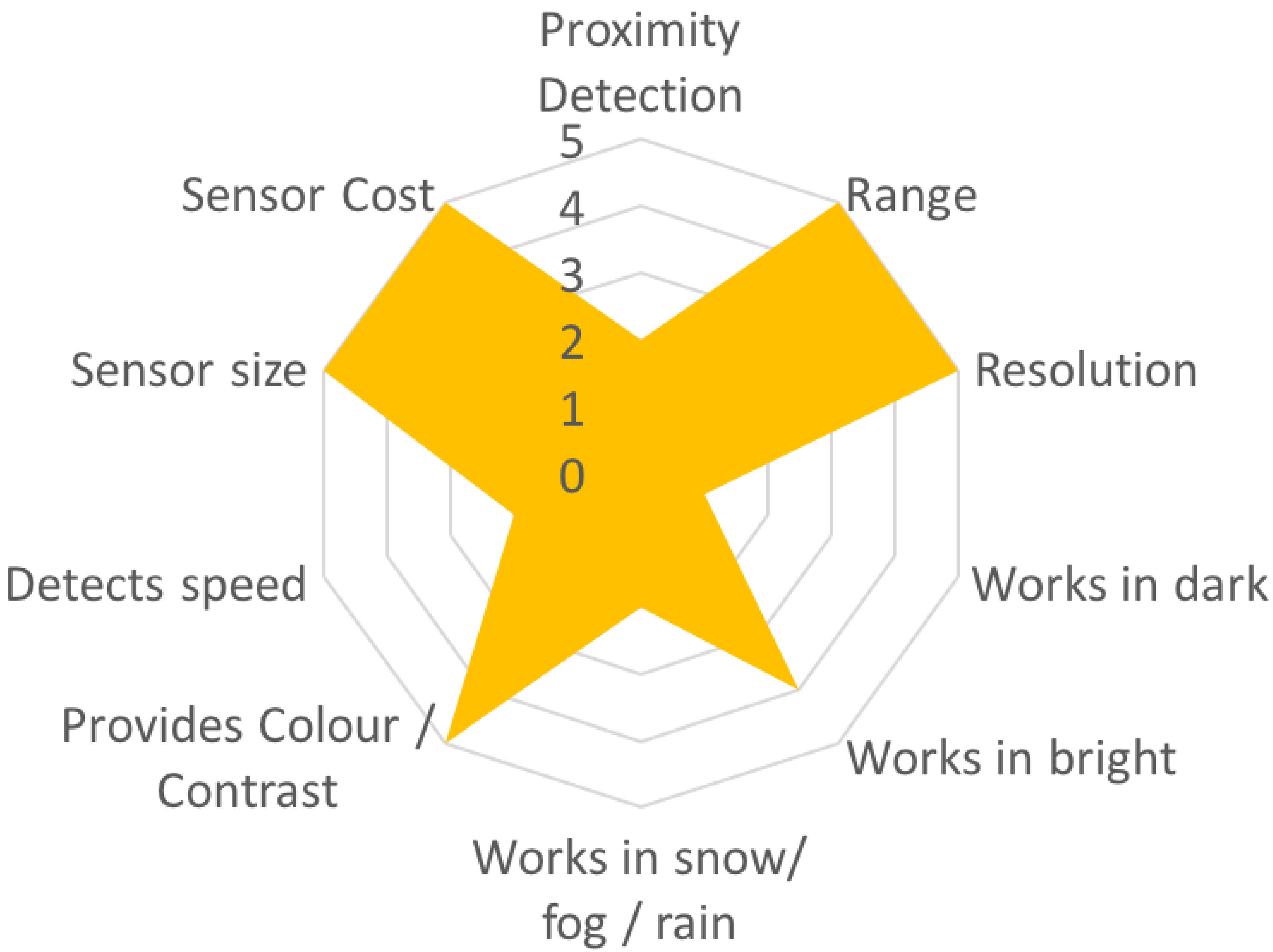
https://cleantechnica.com/2016/07/29/tesla-google-disagree-lidar-right/

Ultrasonic



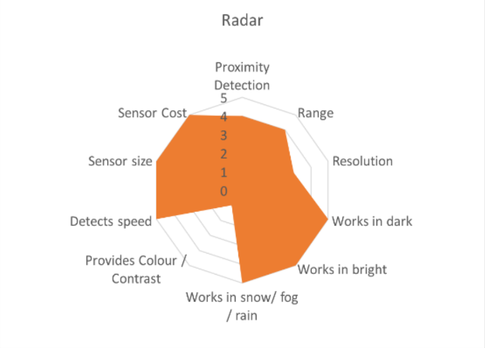
https://cleantechnica.com/2016/07/29/tesla-google-disagree-lidar-right/

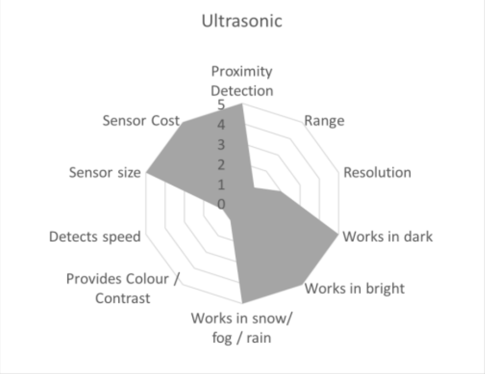
Passive Visual

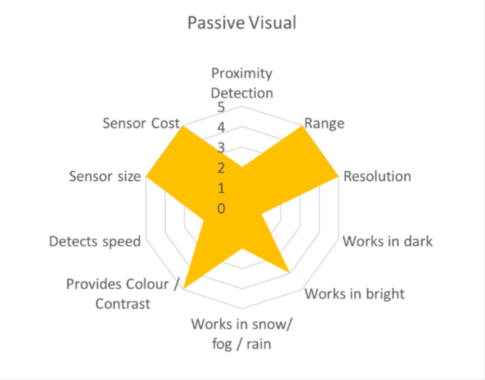


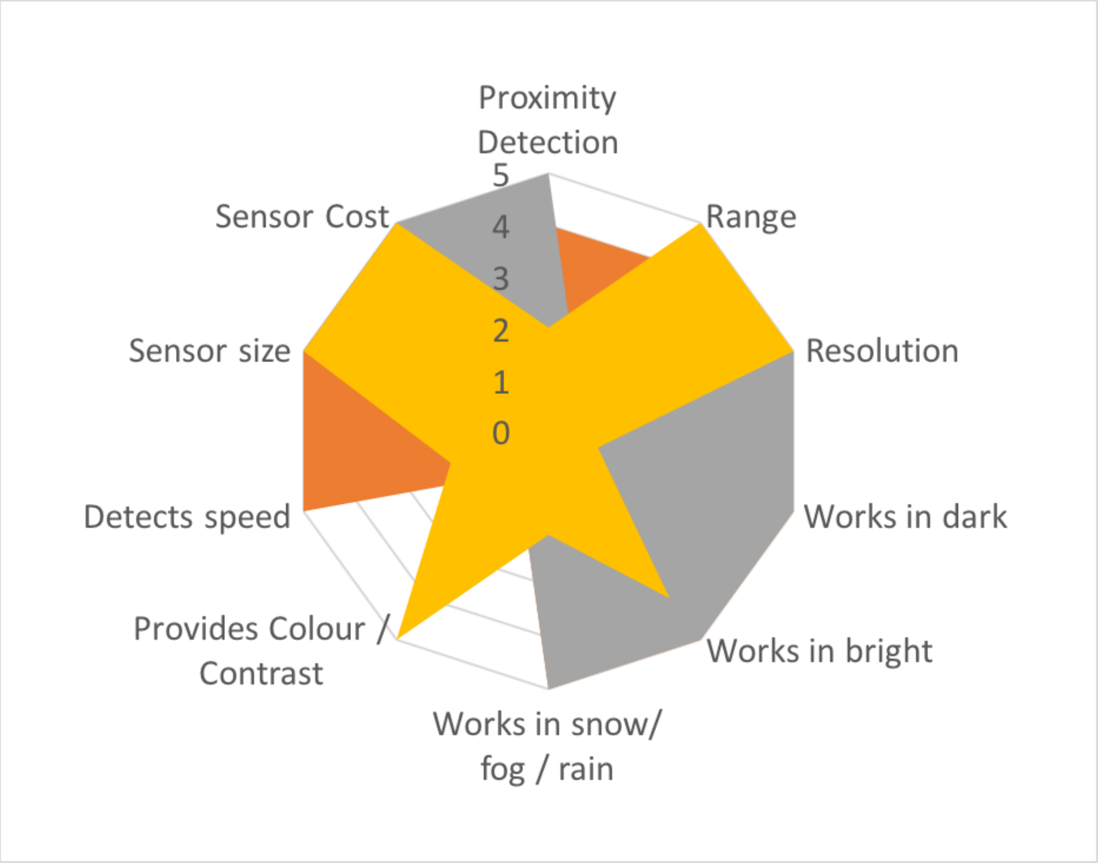
https://cleantechnica.com/2016/07/29/tesla-google-disagree-lidar-right/

Sensor Fusion


Radar


Ultrasonic


Passive Visual



https://cleantechnica.com/2016/07/29/tesla-google-disagree-lidar-right/

Two Approaches to Self-Driving

- Lidar camp
  - Use Lidar and detailed 3D map
  - Good: accurate, explainable
  - Bad: expensive (both Lidar and the map)
- Camera camp
  - Use camera as the primary sensor (like human)
  - Good: cheap(ish)
  - Bad: not accurate, not explainable

Tesla Autopilot Sensors

Rearward Looking Side Cameras
Max distance 100m

Wide Forward Camera
Max distance 60m

Main Forward Camera
Max distance 150m

Narrow Forward Camera
Max distance 250m

Rear View Camera
Max distance 50m

Ultrasonics
Max distance 8m

Forward Looking Side Cameras
Max distance 80m

Radar
Max distance 160m

https://www.tesla.com/autopilot

Tesla Autopilot Sensors

Wide, Main and Narrow Forward Cameras

Three cameras mounted behind the windshield provide broad visibility in front of the car, and focused, long-range detection of distant objects.

Wide

120 degree fisheye lens captures traffic lights, obstacles cutting into the path of travel and objects at close range. Particularly useful in urban, low speed maneuvering.

Main

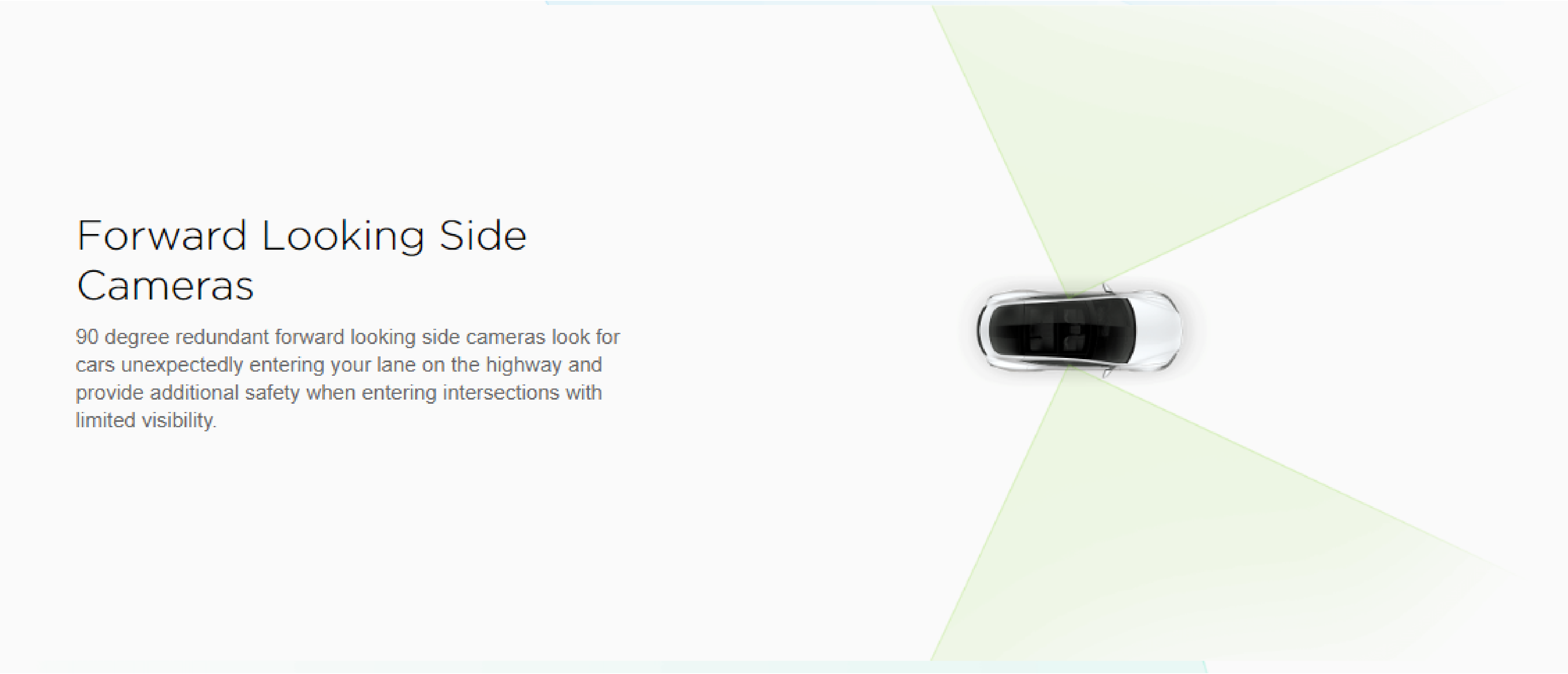
Covers a broad spectrum of use cases.

Narrow

Provides a focused, long-range view of distant features. Useful in high-speed operation.

https://www.tesla.com/autopilot

Tesla Autopilot Sensors

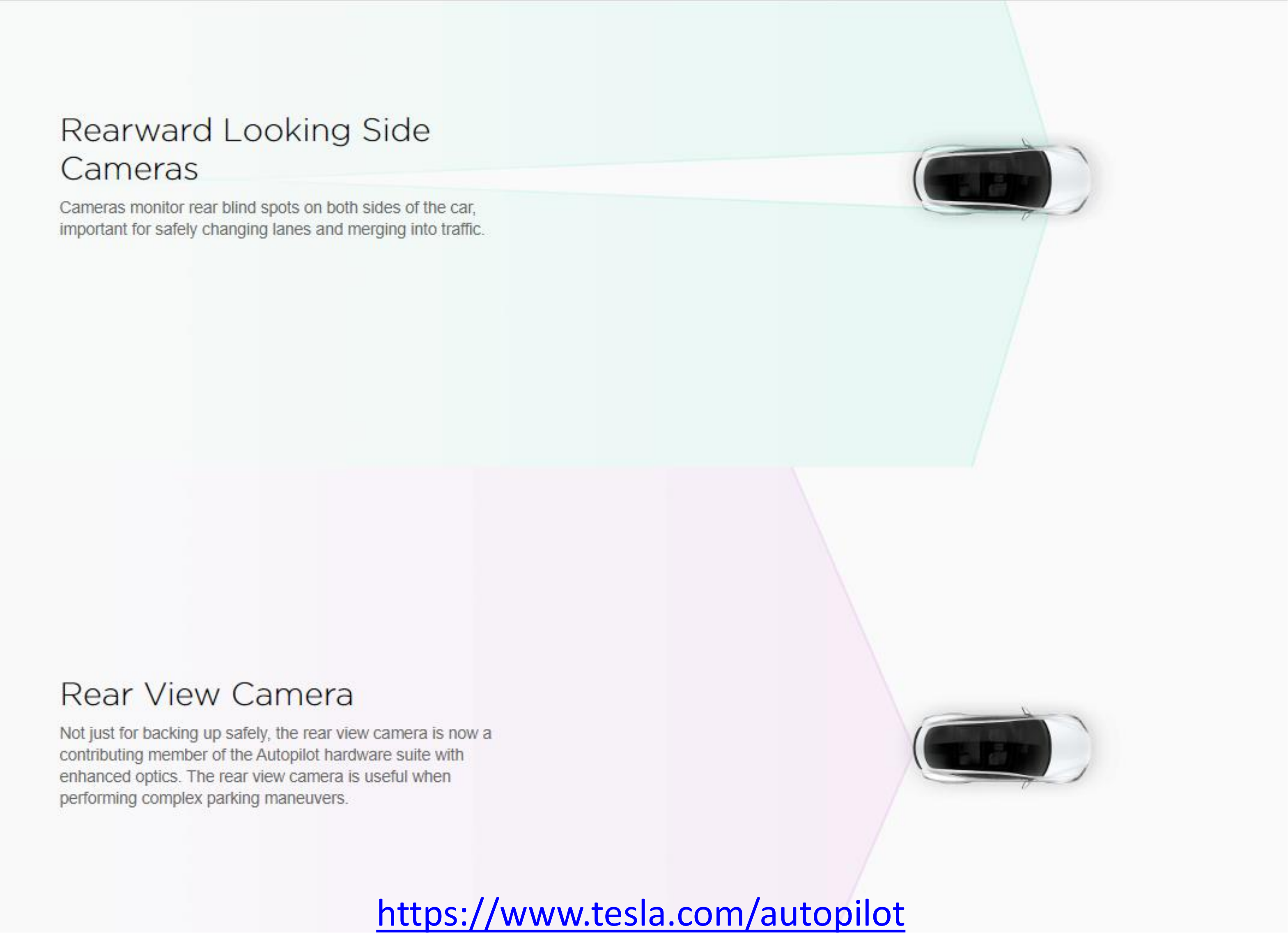


Forward Looking Side Cameras

90 degree redundant forward looking side cameras look for cars unexpectedly entering your lane on the highway and provide additional safety when entering intersections with limited visibility.

https://www.tesla.com/autopilot

Tesla Autopilot Sensors



Rearward Looking Side Cameras

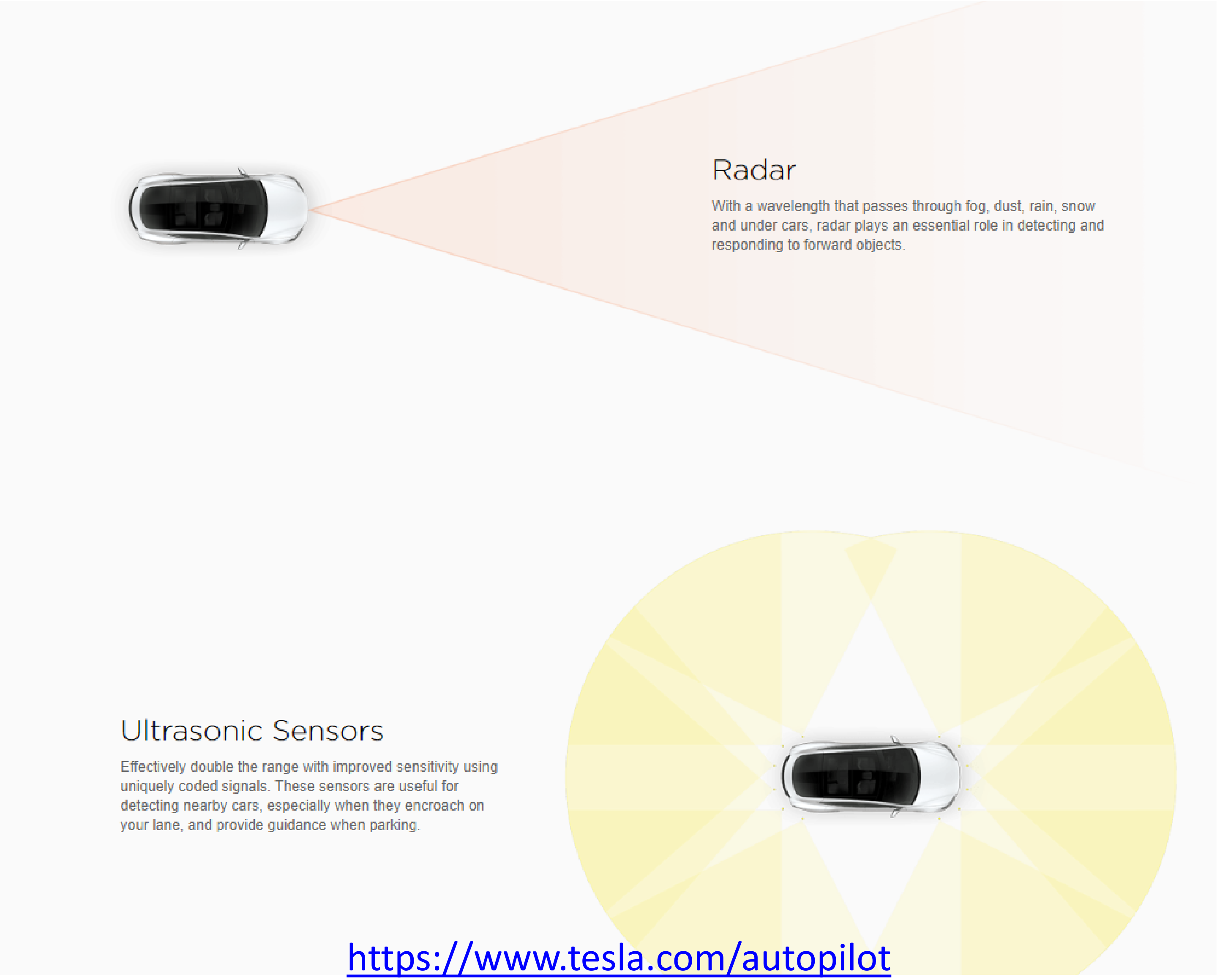
Cameras monitor rear blind spots on both sides of the car, important for safely changing lanes and merging into traffic.

Rear View Camera

Not just for backing up safely, the rear view camera is now a contributing member of the Autopilot hardware suite with enhanced optics. The rear view camera is useful when performing complex parking maneuvers.

https://www.tesla.com/autopilot

Tesla Autopilot Sensors



Radar

With a wavelength that passes through fog, dust, rain, snow and under cars, radar plays an essential role in detecting and responding to forward objects.

Ultrasonic Sensors

Effectively double the range with improved sensitivity using uniquely coded signals. These sensors are useful for detecting nearby cars, especially when they encroach on your lane, and provide guidance when parking.

https://www.tesla.com/autopilot

Design Issues with Sensors

- Calibration
- Nonlinearity
- Sampling
- Noise
- Failures
- Sensor Attacks

Sensor Calibration

- A sensor measures a physical quantity x and reports it to be f(x)

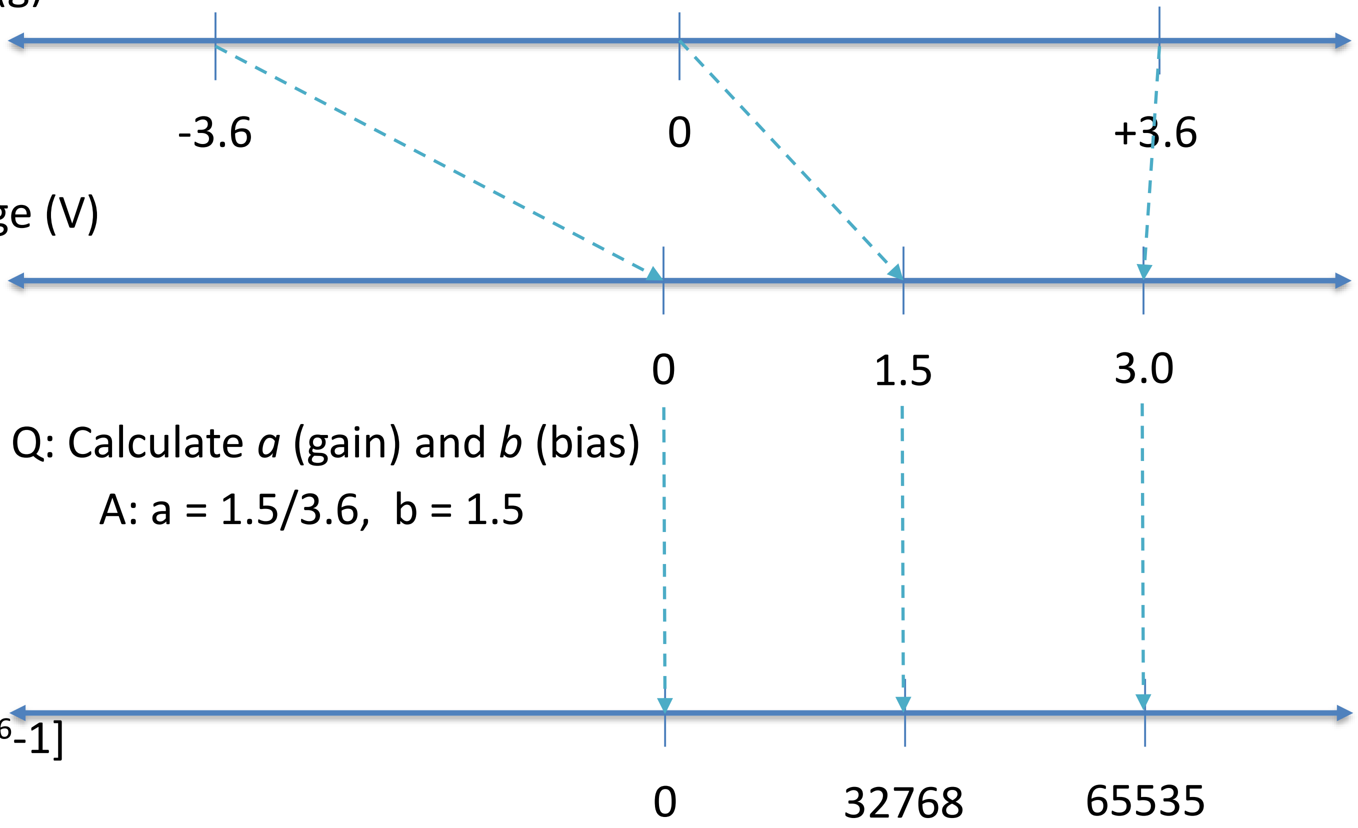
- Linear and affine model

  $f(x) = ax + b$

  where *a* is the **sensitivity (gain)** and *b* is the **bias**

- Calibration: Determine *a* and *b*

Sensor Calibration



Acceleration (g)
x

-3.6
0
+3.6

Measured voltage (V)
f(x)

0
1.5
3.0

f(x) = ax + b

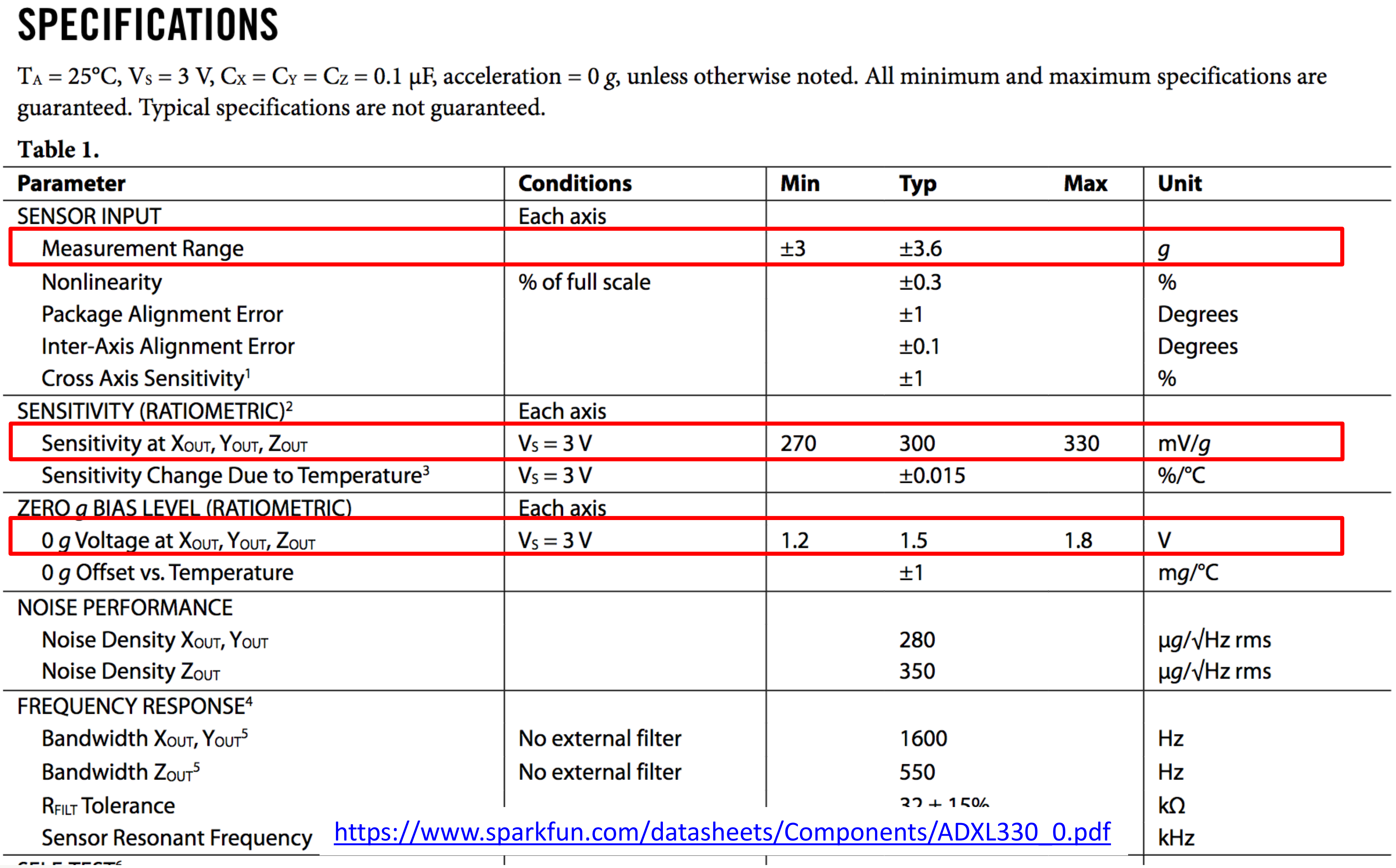
Q: Calculate *a* (gain) and *b* (bias)

A: a = 1.5/3.6, b = 1.5

16 bit ADC
[0,3v] -> [0, 2^{16}-1]

0
32768
65535

Analog Devices ADXL330 Data Sheet



SPECIFICATIONS

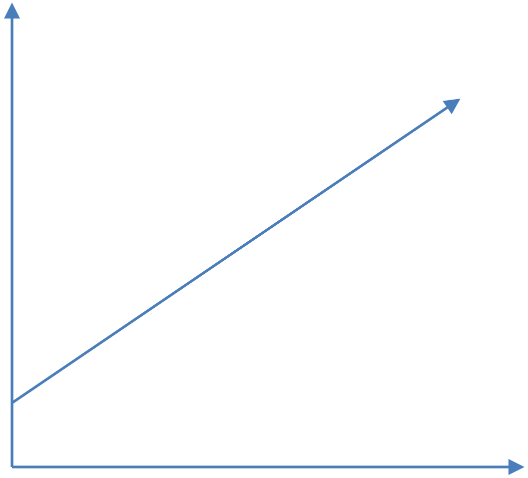
$T_A = 25°C$, $V_S = 3$ V, $C_X = C_Y = C_Z = 0.1$ µF, acceleration = 0 *g*, unless otherwise noted. All minimum and maximum specifications are guaranteed. Typical specifications are not guaranteed.

Table 1.

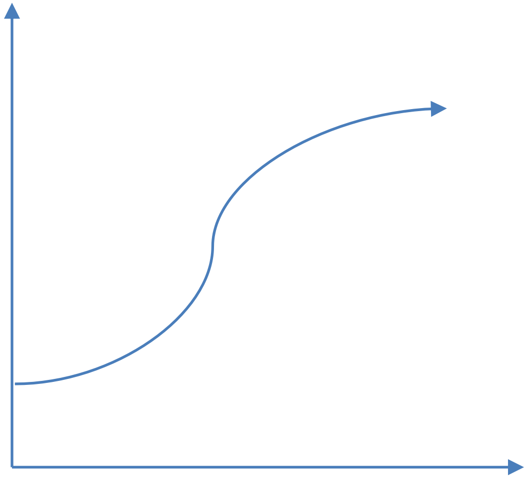
Parameter	Conditions	Min	Typ	Max	Unit
SENSOR INPUT	Each axis				
Measurement Range		±3	±3.6		*g*
Nonlinearity	% of full scale		±0.3		%
Package Alignment Error			±1		Degrees
Inter-Axis Alignment Error			±0.1		Degrees
Cross Axis Sensitivity[1]			±1		%
SENSITIVITY (RATIOMETRIC)[2]	Each axis				
Sensitivity at X_{OUT}, Y_{OUT}, Z_{OUT}	$V_S = 3$ V	270	300	330	mV/*g*
Sensitivity Change Due to Temperature[3]	$V_S = 3$ V		±0.015		%/°C
ZERO *g* BIAS LEVEL (RATIOMETRIC)	Each axis				
0 *g* Voltage at X_{OUT}, Y_{OUT}, Z_{OUT}	$V_S = 3$ V	1.2	1.5	1.8	V
0 *g* Offset vs. Temperature			±1		m*g*/°C
NOISE PERFORMANCE					
Noise Density X_{OUT}, Y_{OUT}			280		µ*g*/√Hz rms
Noise Density Z_{OUT}			350		µ*g*/√Hz rms
FREQUENCY RESPONSE[4]					
Bandwidth X_{OUT}, Y_{OUT}[5]	No external filter		1600		Hz
Bandwidth Z_{OUT}[5]	No external filter		550		Hz
R_{FILT} Tolerance			32 ± 15%		kΩ
Sensor Resonant Frequency					kHz
SELF TEST[6]					

https://www.sparkfun.com/datasheets/Components/ADXL330_0.pdf

Nonlinearity

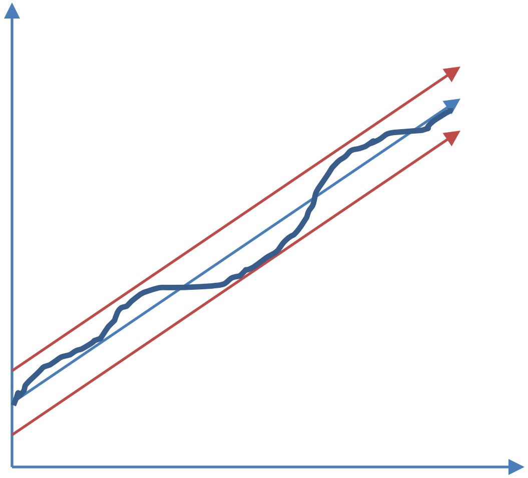


Linear

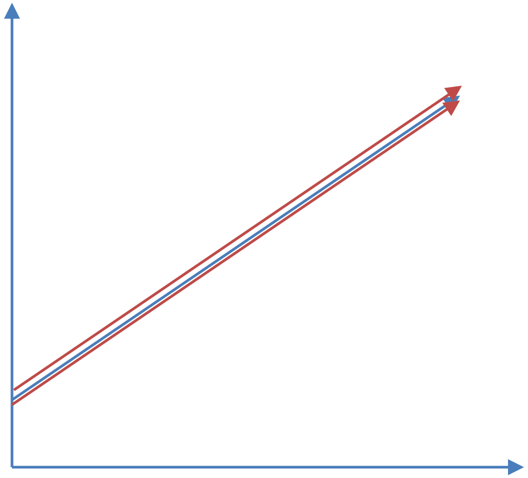


Non-linear

Nonlinearity

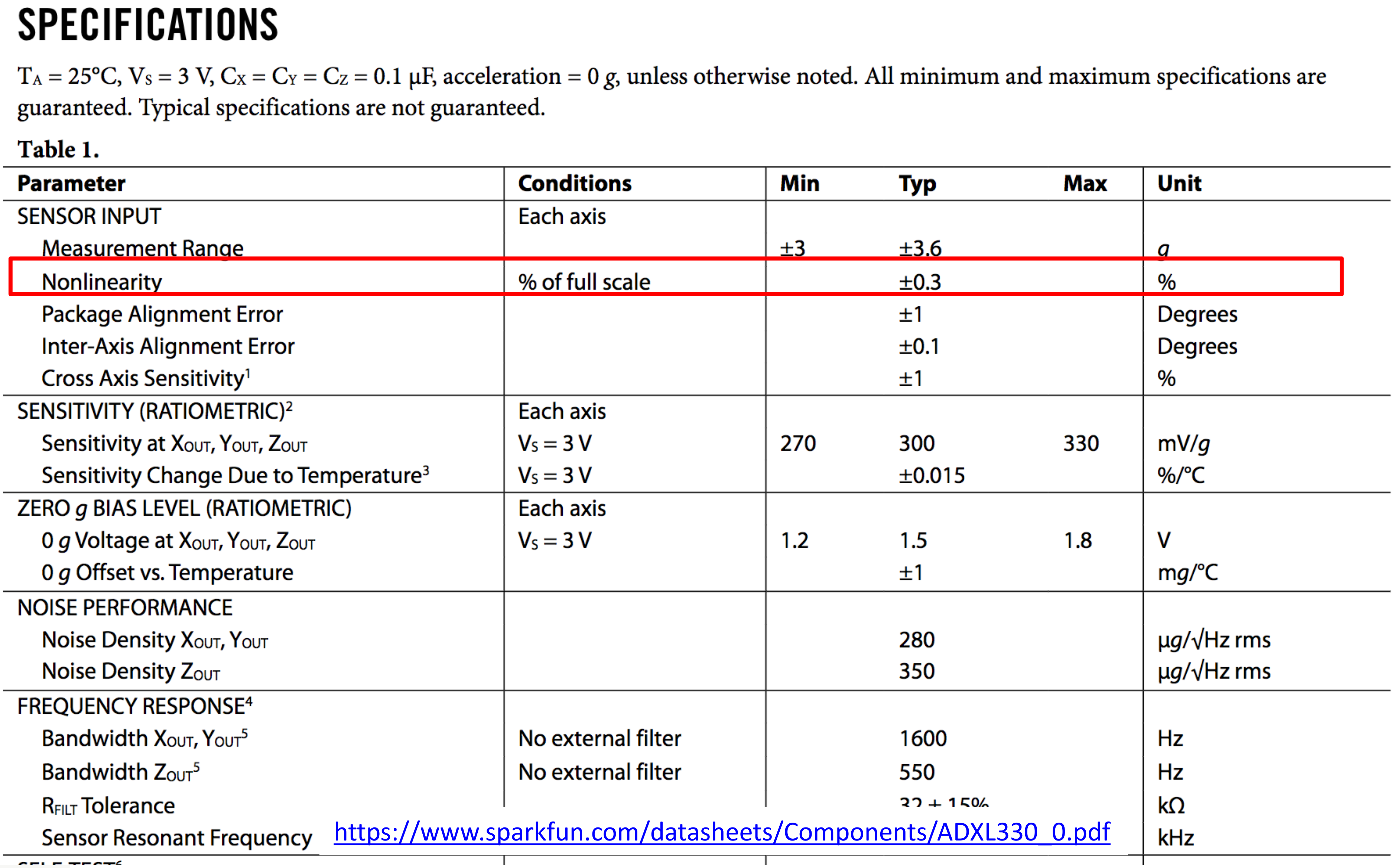


Non-linearity=+-5%



Non-linearity=+-0.5%

Analog Devices ADXL330 Data Sheet



SPECIFICATIONS

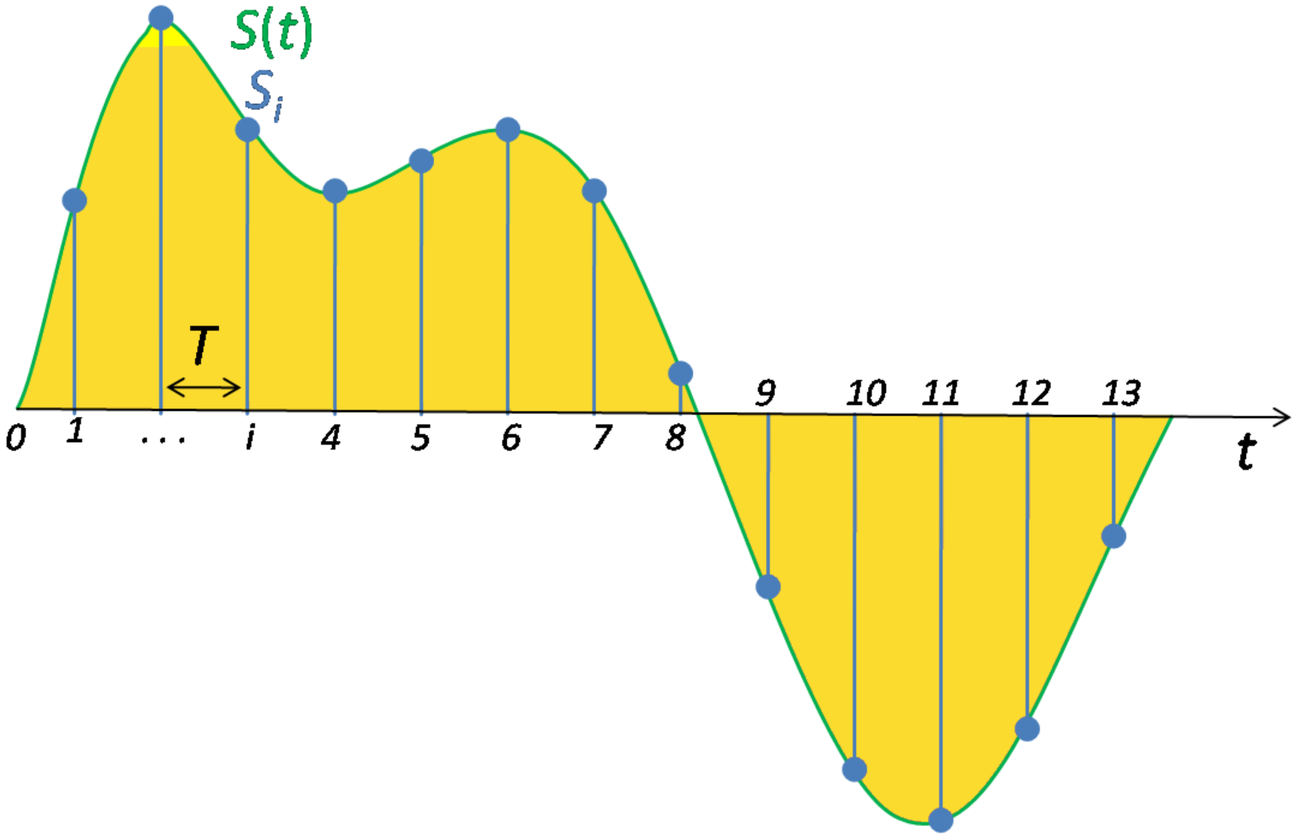
T_A = 25°C, V_S = 3 V, C_X = C_Y = C_Z = 0.1 μF, acceleration = 0 *g*, unless otherwise noted. All minimum and maximum specifications are guaranteed. Typical specifications are not guaranteed.

Table 1.

Parameter	**Conditions**	**Min**	**Typ**	**Max**	**Unit**
SENSOR INPUT	Each axis				
Measurement Range		±3	±3.6		*g*
Nonlinearity	% of full scale		±0.3		%
Package Alignment Error			±1		Degrees
Inter-Axis Alignment Error			±0.1		Degrees
Cross Axis Sensitivity[1]			±1		%
SENSITIVITY (RATIOMETRIC)[2]	Each axis				
Sensitivity at X_{OUT}, Y_{OUT}, Z_{OUT}	V_S = 3 V	270	300	330	mV/*g*
Sensitivity Change Due to Temperature[3]	V_S = 3 V		±0.015		%/°C
ZERO *g* BIAS LEVEL (RATIOMETRIC)	Each axis				
0 *g* Voltage at X_{OUT}, Y_{OUT}, Z_{OUT}	V_S = 3 V	1.2	1.5	1.8	V
0 *g* Offset vs. Temperature			±1		m*g*/°C
NOISE PERFORMANCE					
Noise Density X_{OUT}, Y_{OUT}			280		μ*g*/√Hz rms
Noise Density Z_{OUT}			350		μ*g*/√Hz rms
FREQUENCY RESPONSE[4]					
Bandwidth X_{OUT}, Y_{OUT}[5]	No external filter		1600		Hz
Bandwidth Z_{OUT}[5]	No external filter		550		Hz
R_{FILT} Tolerance			32 ± 15%		kΩ
Sensor Resonant Frequency					kHz

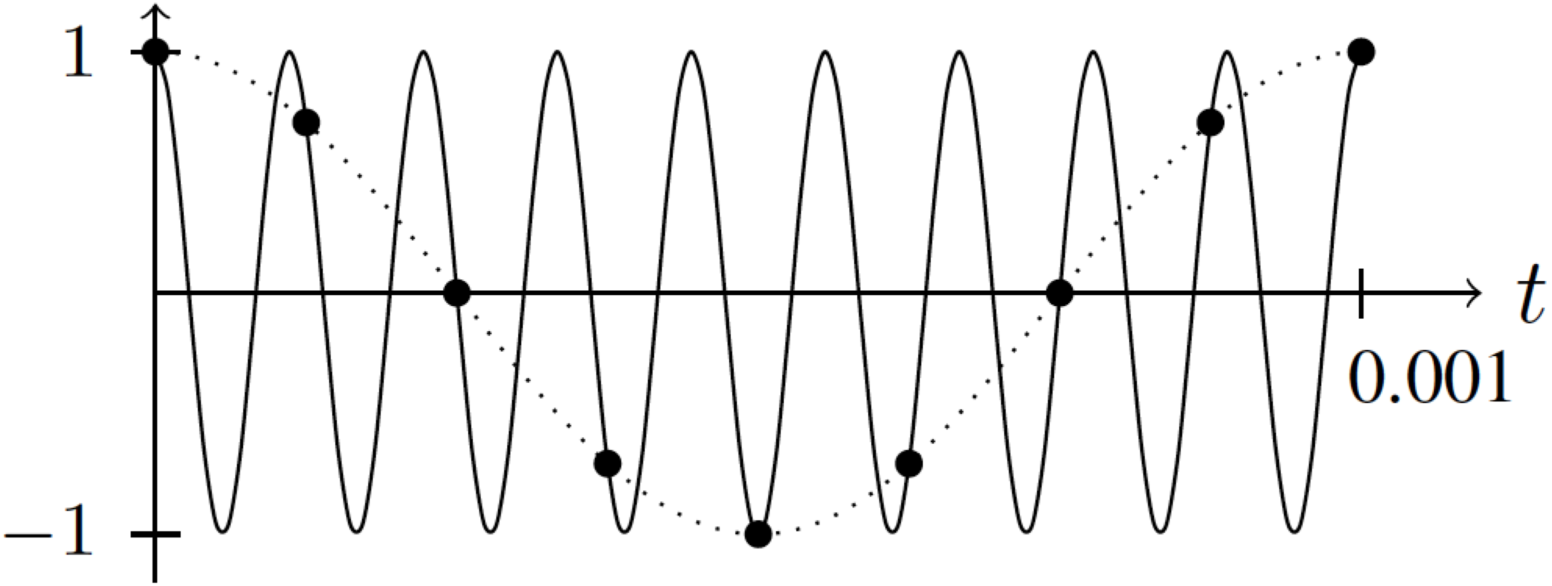
https://www.sparkfun.com/datasheets/Components/ADXL330_0.pdf

Sampling



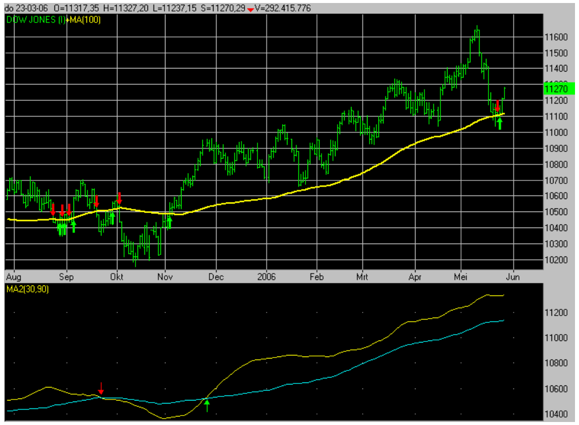
This Photo by Unknown Author is licensed under CC BY-SA

Aliasing



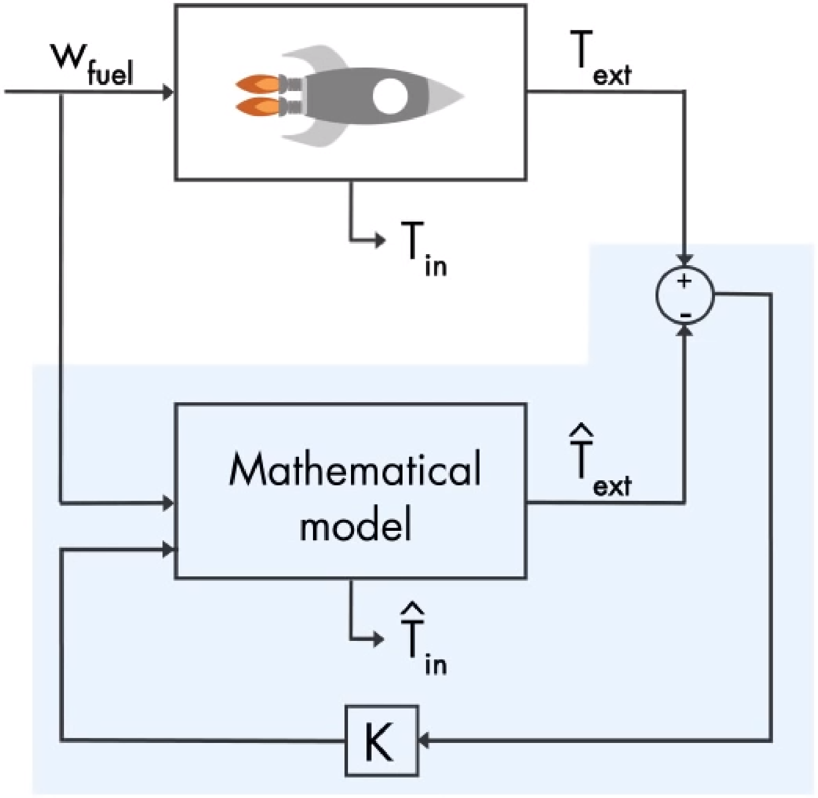
Noise

- All sensors are noisy (at varying degrees)
- Filtering improve robustness
  - Low/high pass filters (cut off low or high values of certain thresholds)
  - Exponential weighted moving average (EWMA) filter: $S(t) = a * Y(t) + (1-a) * S(t-1)$
  - …



Kalman Filter

- Estimating variables that cannot be directly measured using indirect measurements
- Model based optimal estimation algorithm



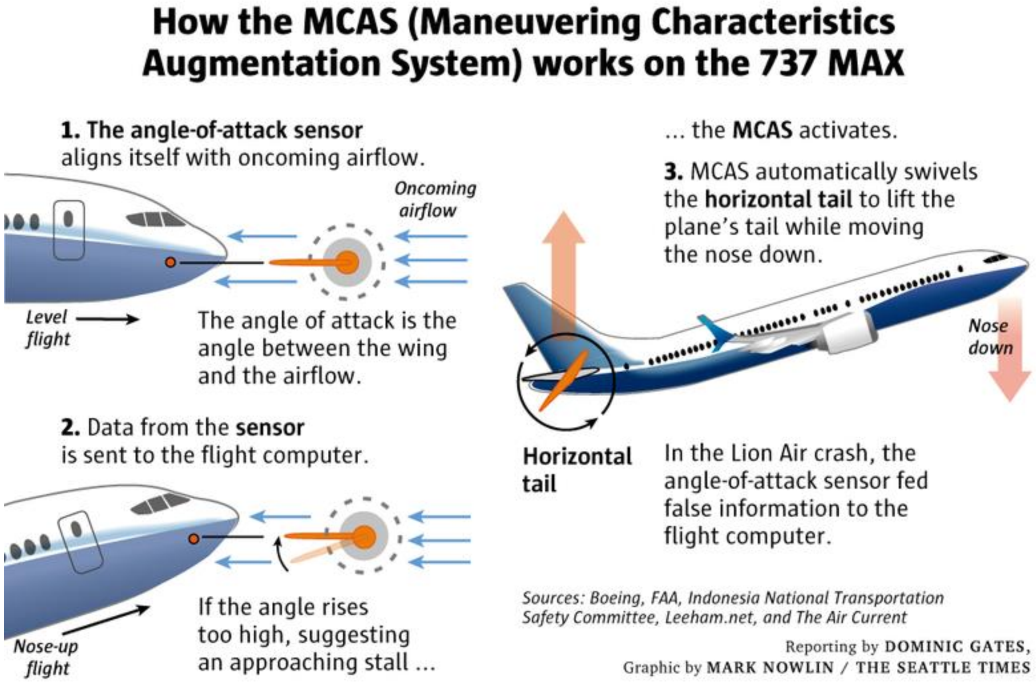
https://www.youtube.com/watch?v=4OerJmPpkRg

Sensor Failures

- Sensors are physical devices and thus can fail
  - Some are more prone than others, but all can fail
- Common causes
  - Wear and tear, physical damage
  - Obstruction (e.g., dust), bad weathers
  - …
- You cannot assume all sensors of a system will work all the times.

Ethiopian Air 302 (2019)

- MCAS relied on a single sensor
  - Single source of failure



How the MCAS (Maneuvering Characteristics Augmentation System) works on the 737 MAX

1. The angle-of-attack sensor aligns itself with oncoming airflow.

The angle of attack is the angle between the wing and the airflow.

2. Data from the **sensor** is sent to the flight computer.

If the angle rises too high, suggesting an approaching stall …

… the **MCAS** activates.

3. MCAS automatically swivels the **horizontal tail** to lift the plane's tail while moving the nose down.

In the Lion Air crash, the angle-of-attack sensor fed false information to the flight computer.

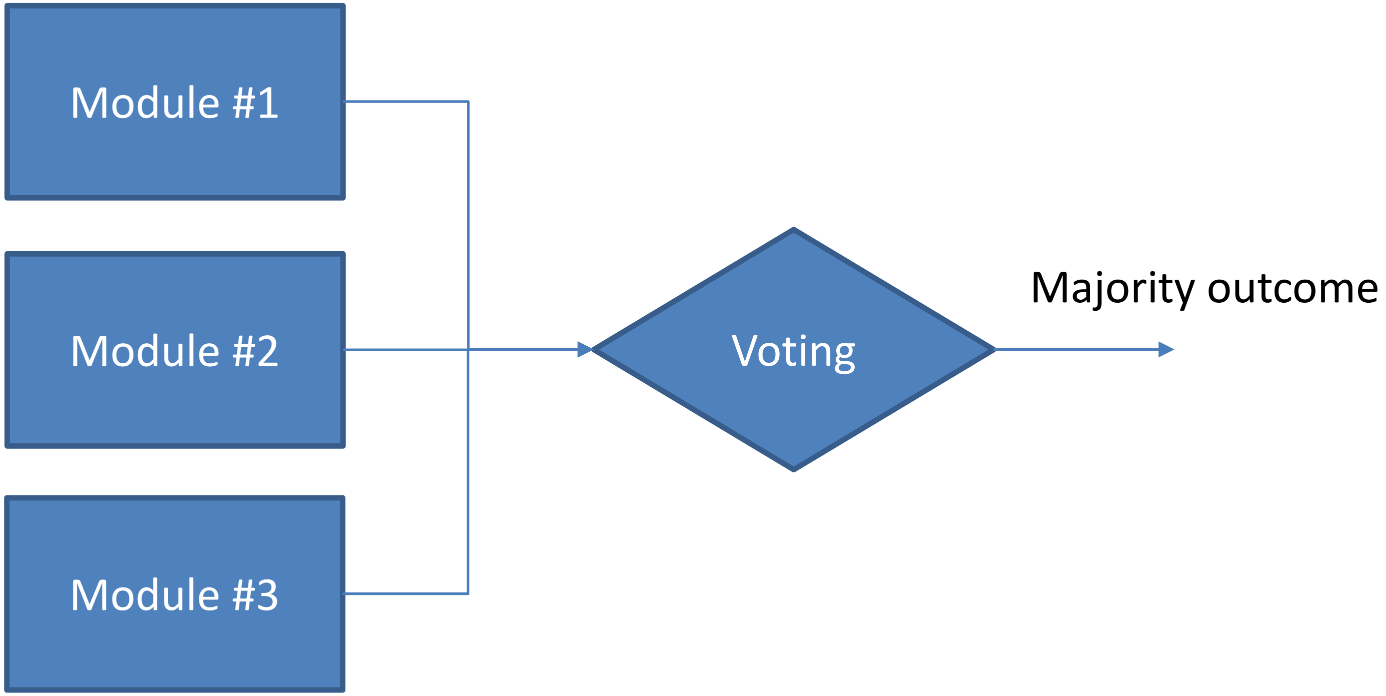
Sources: Boeing, FAA, Indonesia National Transportation Safety Committee, Leeham.net, and The Air Current

Reporting by DOMINIC GATES, Graphic by MARK NOWLIN / THE SEATTLE TIMES

https://www.seattletimes.com/business/boeing-aerospace/failed-certification-faa-missed-safety-issues-in-the-737-max-system-implicated-in-the-lion-air-crash

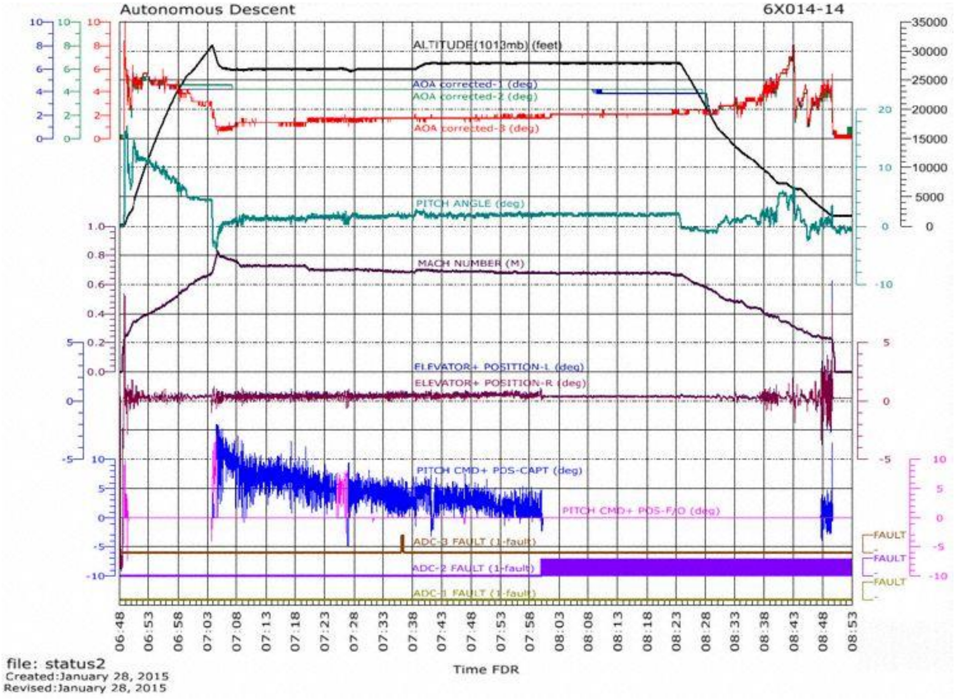
Redundancy

- Triple Modular Redundancy (TMR)



Lufthansa A321 (2014)

- Three redundant AoA sensors, but two freeze up simultaneously.
- The correct sensor’s outputs were discarded.



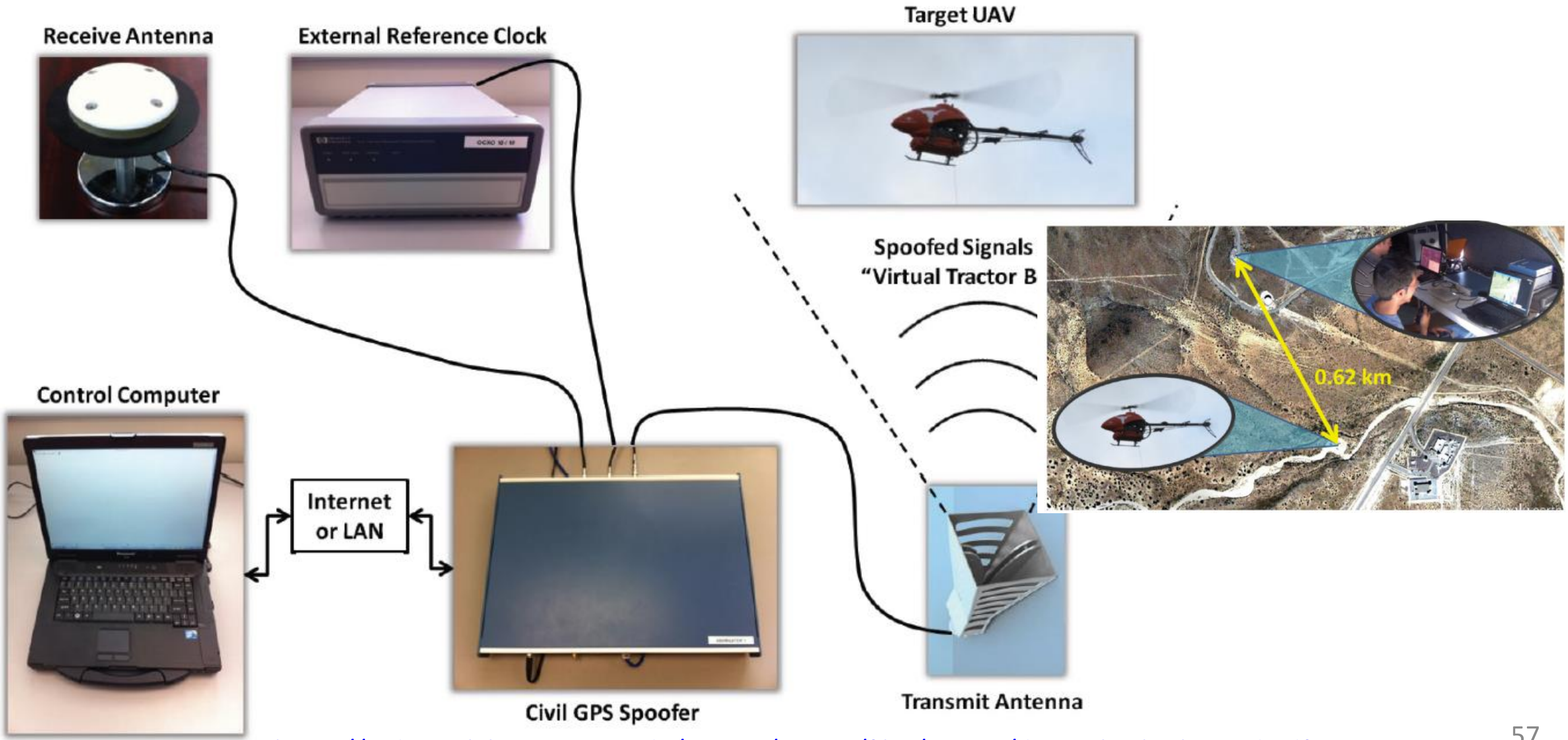
Sensor Attacks

- Hackers may deliberately affect sensor performance

- Examples
  - Drone hack: Spoofing attack demonstration on a civilian unmanned aerial vehicle. GPS World, August 2012
  - Rocking Drones with Intentional Sound Noise on Gyroscopic Sensors, USENIX Security, 2015

Drone GPS Spoofing (2012)

- Fool GPS sensors
  - Attacker can control the trajectory of the UAV



https://radionavlab.ae.utexas.edu/images/stories/files/papers/drone_hack_shepard.pdf

Sound Attack on IMU Sensor (2015)

https://youtu.be/k1FcDTeOSVI?t=821

Sensor Input Spoofing

Attack & Defense

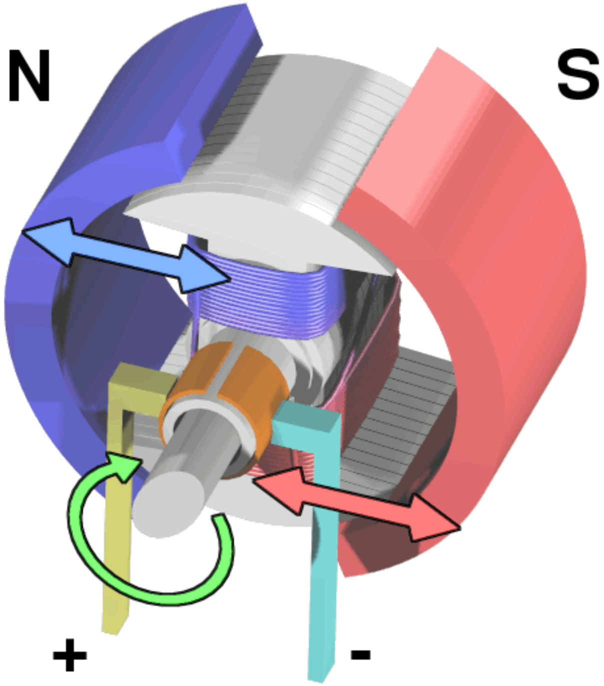
Drew Davidson
University of Kansas EECS
Cybersecurity @ ITTC

Actuators

- DC motors
- PWM

DC Motor

- Transforms electrical energy into mechanical energy
  - Lawrence law
  - Periodically change the direction of current flow
- Brushed DC motor
  - Use mechanical switches to change current flow
- Brushless DC motor
  - Use electronic mechanisms to change current flow

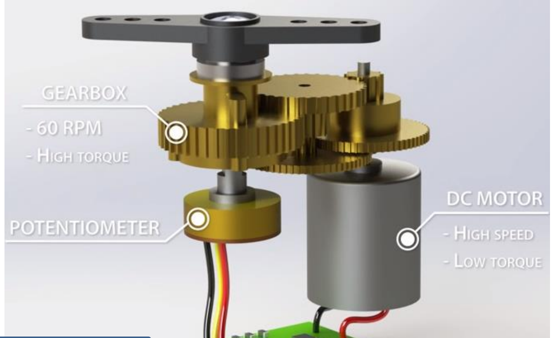


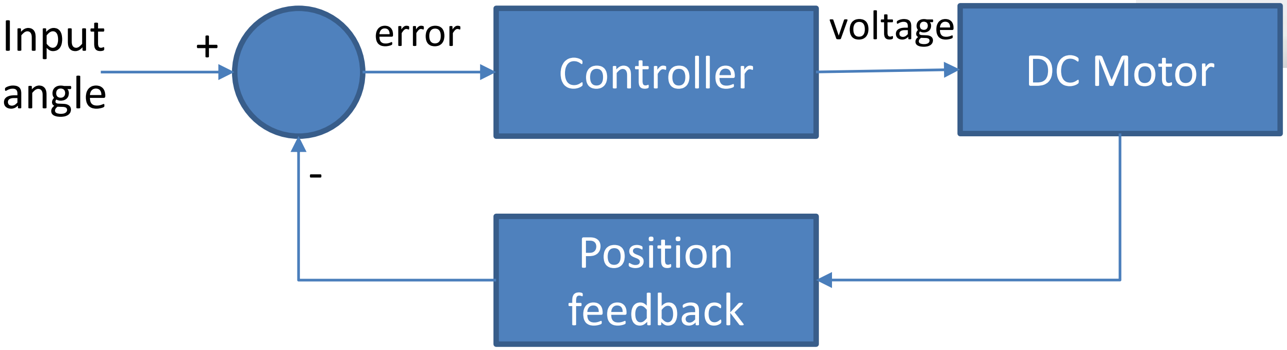
This Photo by Unknown Author is licensed under CC BY-SA

How do DC motors work?:
https://www.youtube.com/watch?v=LAtPHANEfQo
https://www.youtube.com/watch?v=bCEiOnuODac

Servo Motor

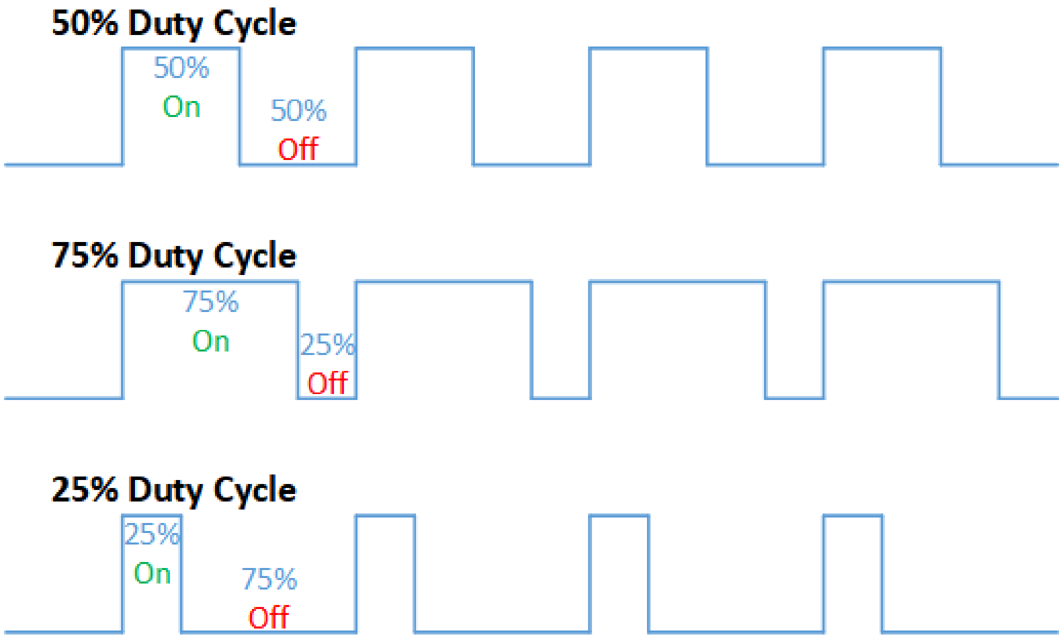
- Precisely control the angle
  - E.g., car steering, robot arm, …
- A closed loop feedback system
  - MCU + sensor + motor





Pulse-Width Modulation (PWM)

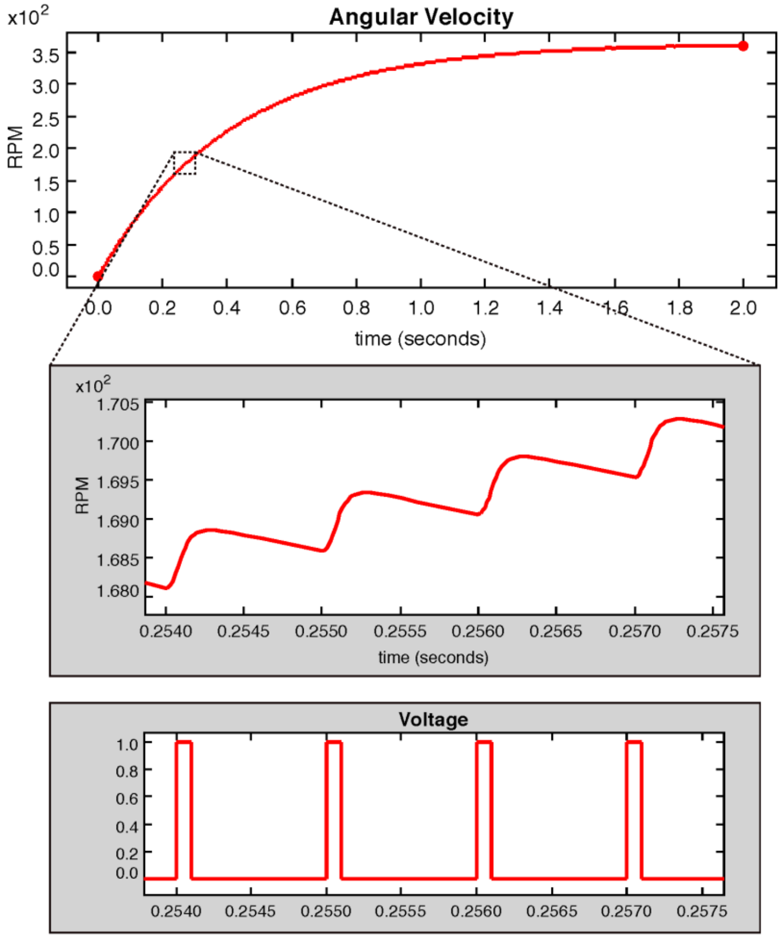
- Encode analog signal using digital outputs



CC BY-SA 4.0. by [Thewrightstuff]

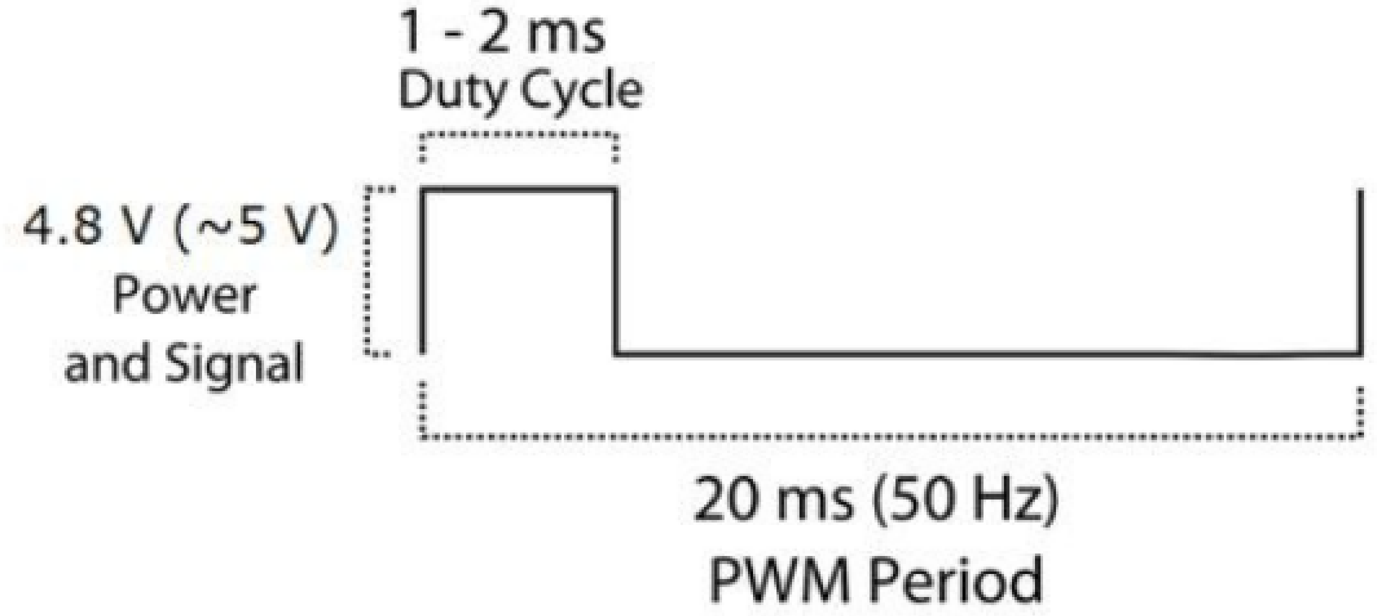
Pulse-Width Modulation (PWM)

- Actuators need time to react to input change
- Resulting gradual changes makes PWM effective for control
- Rapid on/off control is called as "bang-bang" control



Pulse-Width Modulation (PWM)

- PWM based servo motor control
  - Angle = F(duty cycle length)
    - E.g., 1ms = 0 degree, 1.5ms = 90 deg., 2ms = 180 deg.



Summary

- Sensors
  - “Read from physical world”
  - Essential for many (most) embedded systems
  - No sensor is perfect: calibration, nonlinearity, noise, sampling, failure, security and other issues.
- Actuators
  - “Write to physical world”
  - Motors and PWM based control

Acknowledgements

- These slides contain material developed by
  - Edward A. Lee and Prabal Dutta (UCB) for EECS149/249A
  - Lex Fridman (MIT) for 6.S094