

# Development of intelligent systems (RInS)

## Robot sensors and TurtleBot

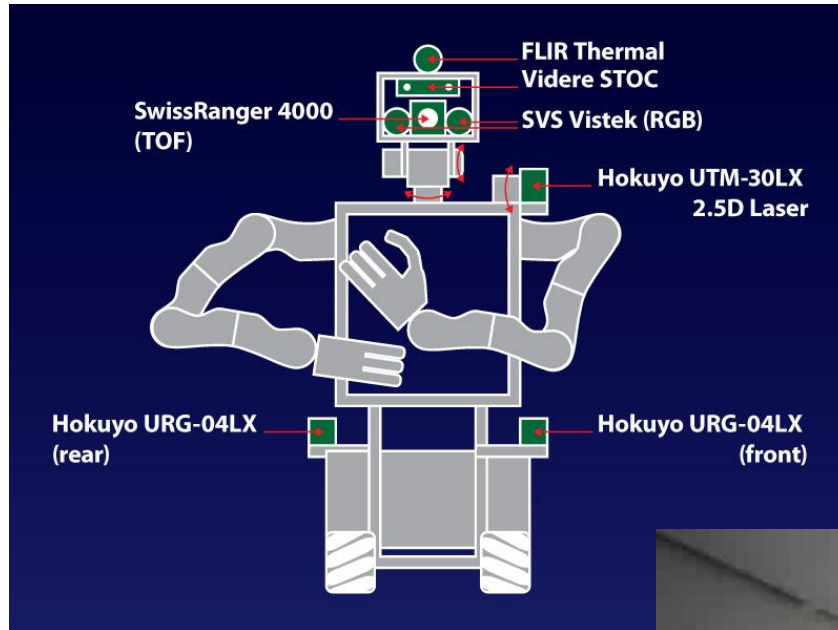
Danijel Skočaj

University of Ljubljana

Faculty of Computer and Information Science

Academic year: 2025/26

# Robotic sensors



Sensors

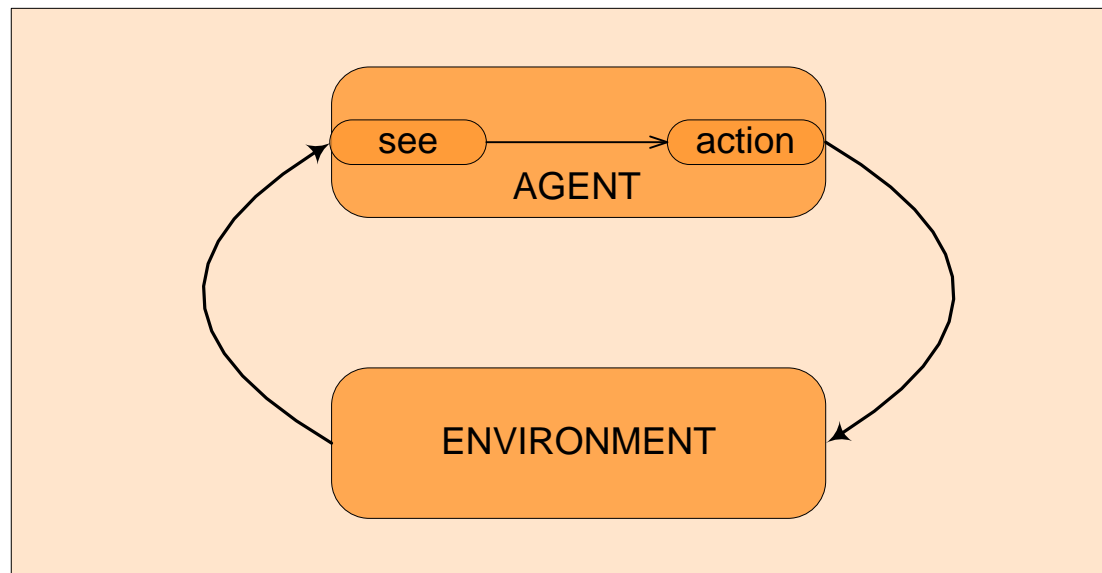
Robot platforms

<http://ias.cs.tum.edu>

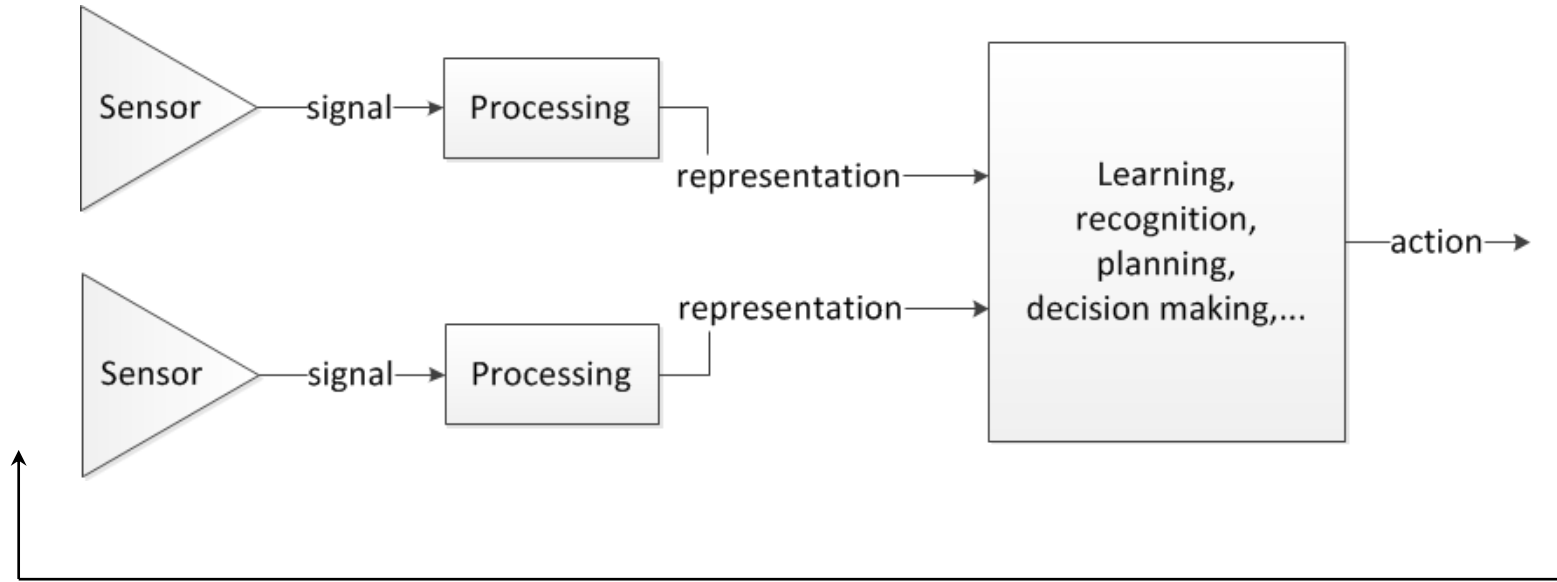


# Sensors

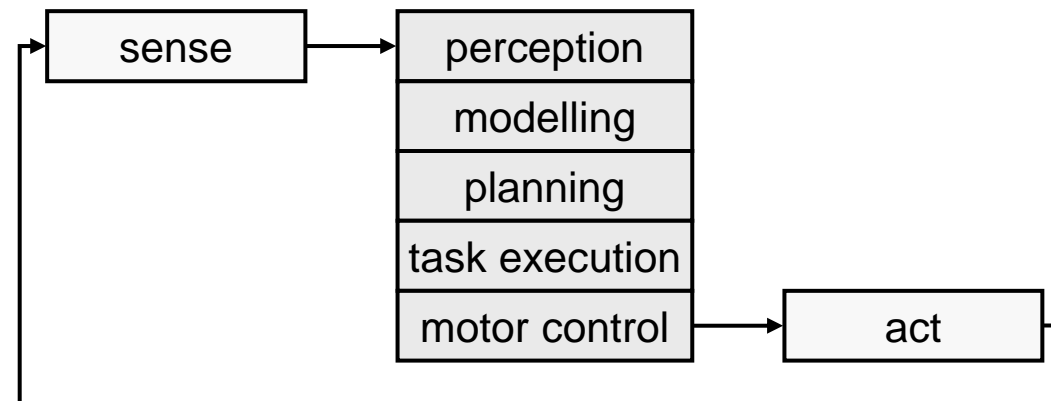
- Equivalent to human senses
- Acquire information from the environment
- Electronic/mechanic/chemical device that maps the attributes of the environment into a quantitative measurement
- Robot can differentiate only between the states in the environment, which can be sensed differently



# Perception action cycle



- Significant abstraction of the real world



# Senses

- Human senses:



- The list of robot senses is much longer!
  - Beyond human capabilities
  - Vision beyond visual spectrum (IR cameras, etc.)
  - Active vision (radar, LIDAR)
  - Hearing beyond the range 20 Hz-20 kHz (ultrasound)
  - Chemical analysis for better taste and smell
  - Measurement of temperature, humidity, illumination, radiation, pressure, volume, position, direction, acceleration, velocity, etc.

# Classification of sensors

---

- Proprioceptive and exteroceptive sensors
  - Proprioceptive: measure internal states of the robot (battery status, position of wheels, angle between the segments in the robot arm)
  - Exteroceptive: measure the state of the environment (majority of the sensors)
- Passive and active sensors
  - Passive: only receive the energy from the environment (e.g., camera)
  - Active: also emit the energy in the environment (e.g., radar)
- Noninvasive and invasive sensors
  - Noninvasive (contactless): no contact with the object
  - Invasive: measurement with contact
- Visual, non-visual

# Classification of sensors

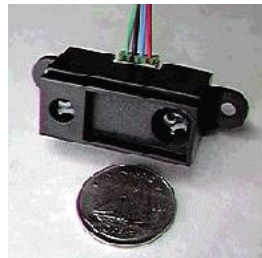
General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Tactile sensors (detection of physical contact or closeness; security switches)	Contact switches, bumpers	EC	P
	Optical barriers	EC	A
	Noncontact proximity sensors	EC	A
Wheel/motor sensors (wheel/motor speed and position)	Brush encoders	PC	P
	Potentiometers	PC	P
	Synchros, resolvers	PC	A
	Optical encoders	PC	A
	Magnetic encoders	PC	A
	Inductive encoders	PC	A
	Capacitive encoders	PC	A
Heading sensors (orientation of the robot in relation to a fixed reference frame)	Compass	EC	P
	Gyroscopes	PC	P
	Inclinometers	EC	A/P

A, active; P, passive; P/A, passive/active; PC, proprioceptive; EC, exteroceptive.

# Classification of sensors

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Ground-based beacons (localization in a fixed reference frame)	GPS	EC	A
	Active optical or RF beacons	EC	A
	Active ultrasonic beacons	EC	A
	Reflective beacons	EC	A
Active ranging (reflectivity, time-of-flight, and geo- metric triangulation)	Reflectivity sensors	EC	A
	Ultrasonic sensor	EC	A
	Laser rangefinder	EC	A
	Optical triangulation (1D)	EC	A
	Structured light (2D)	EC	A
Motion/speed sensors (speed relative to fixed or moving objects)	Doppler radar	EC	A
	Doppler sound	EC	A
Vision-based sensors (visual ranging, whole-image analy- sis, segmentation, object recognition)	CCD/CMOS camera(s) Visual ranging packages Object tracking packages	EC	P

# Sensors in robots



Digital Infrared Ranging



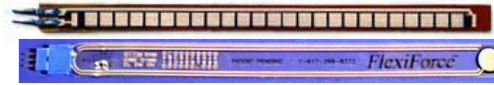
CDS Cell Resistive Light Sensor



Piezo Bend Sensor



Pendulum Resistive Tilt Sensors



Resistive Bend Sensors



Metal Detector



UV Detector



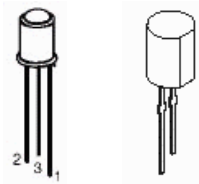
Gas Sensor



Pyroelectric Detector



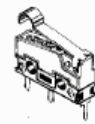
Gieger-Muller Radiation Sensor



IR Pin Diode



IR Sensor w/lens



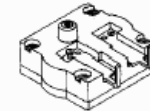
Limit Switch



Mechanical Tilt Sensors



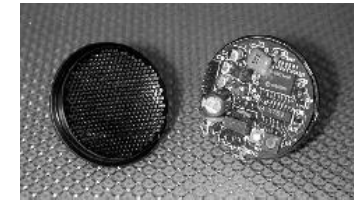
Touch Switch



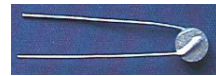
Pressure Switch



Gyro



Miniature Polaroid Sensor



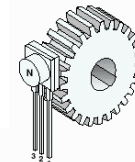
Thyristor



Magnetic Sensor



Magnetic Reed Switch



Hall Effect Magnetic Field Sensors



Polaroid Sensor Board



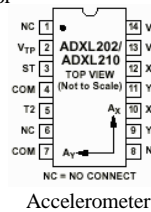
IR Reflection Sensor



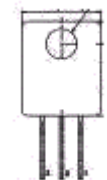
IR Amplifier Sensor



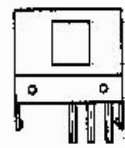
IRDA Transceiver



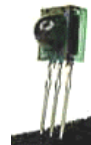
Accelerometer



Lite-On IR Remote Receiver



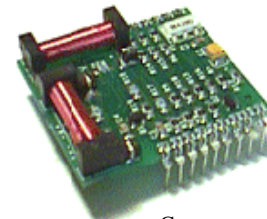
Radio Shack Remote Receiver



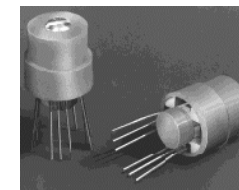
IR Modulator Receiver



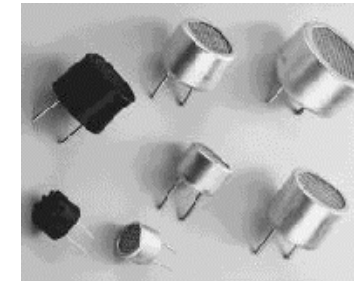
Solar Cell



Compass



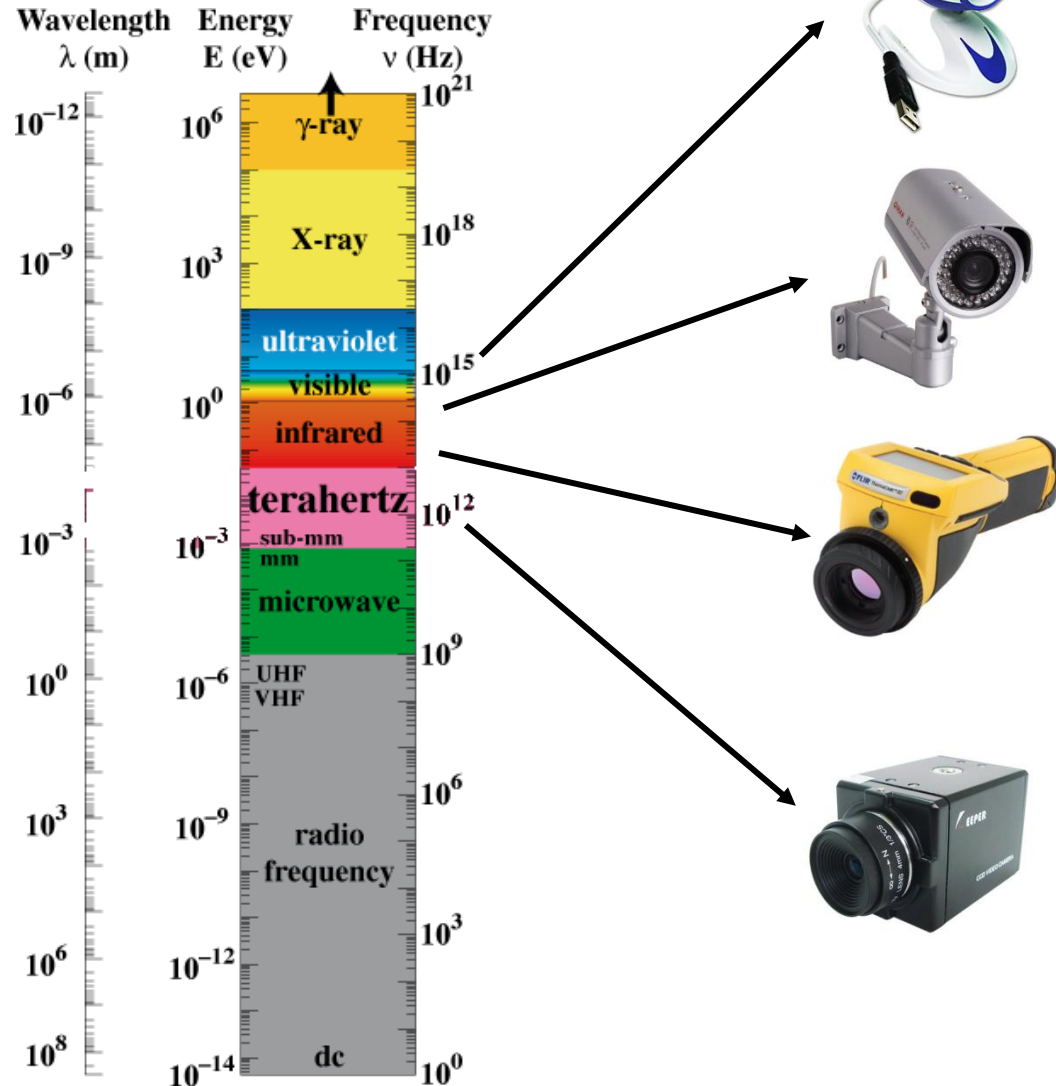
Compass



Piezo Ultrasonic Transducers

# Cameras

## Electromagnetic spectrum



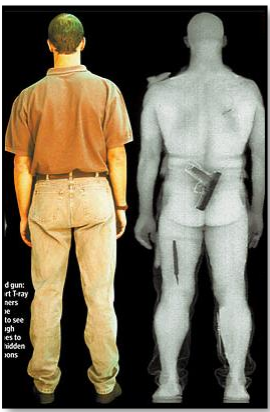
Visual  
"light"



Near infrared  
"light"  
(NIR)



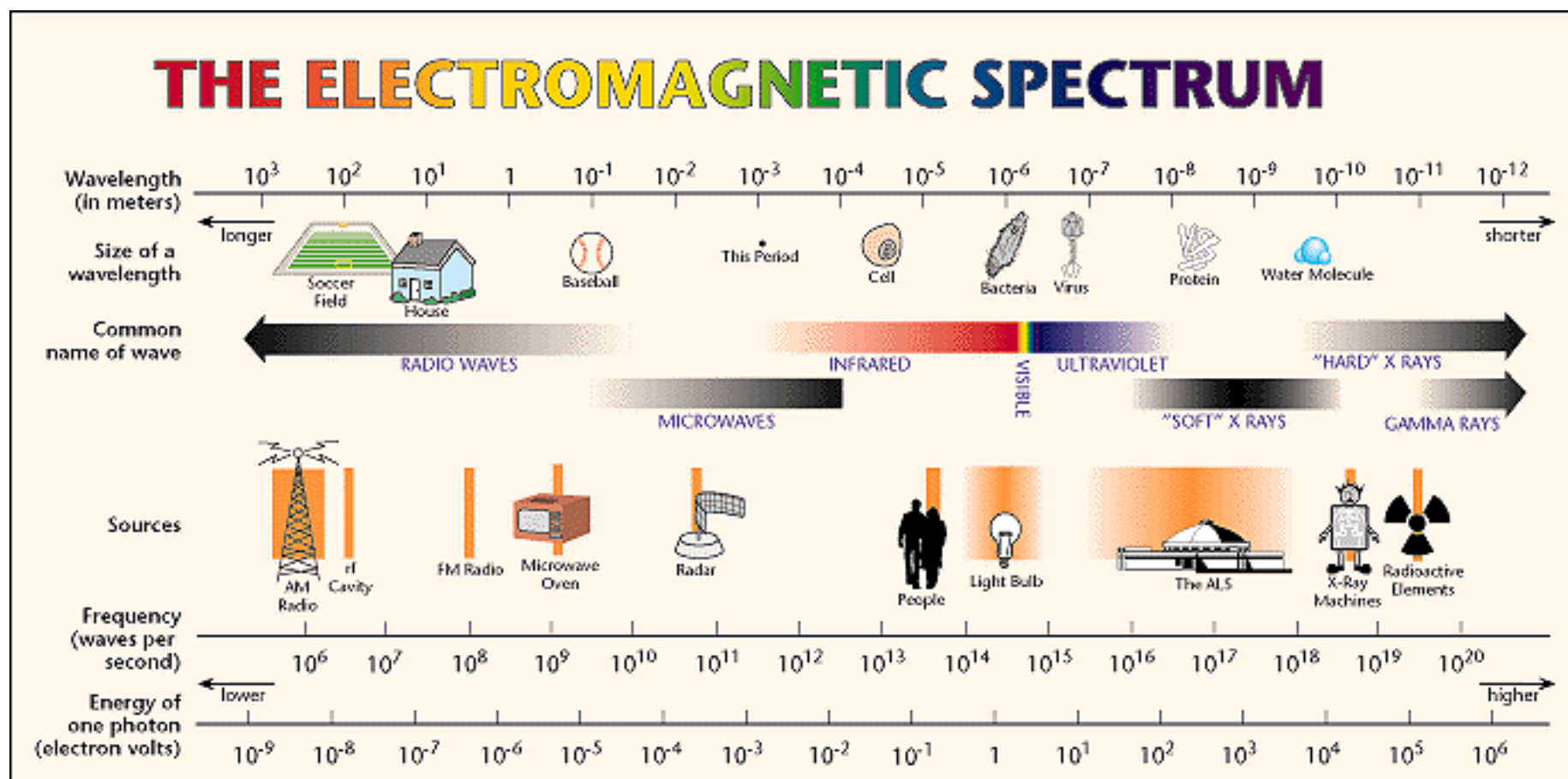
Long-wavelength  
infrared "light"  
(FLIR)



Terahertz  
"light"  
(T-ray)

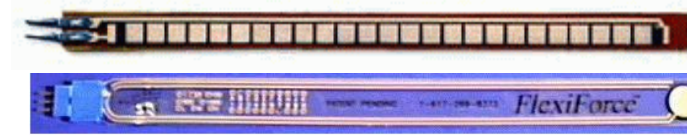


# Sensing EM radiation



# Resistive sensors

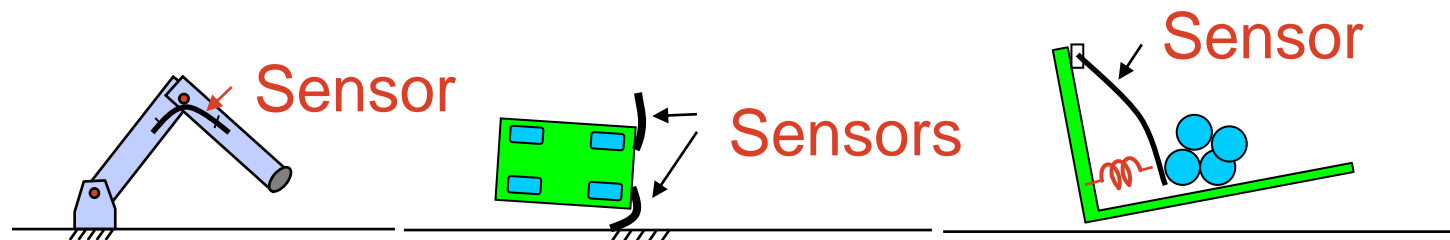
- Band sensor
  - The resistance changes by bending the sensor



- Potentiometer
  - Position sensor in sliding or rotating mechanisms



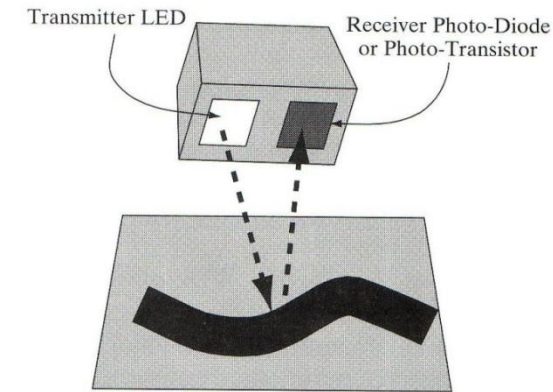
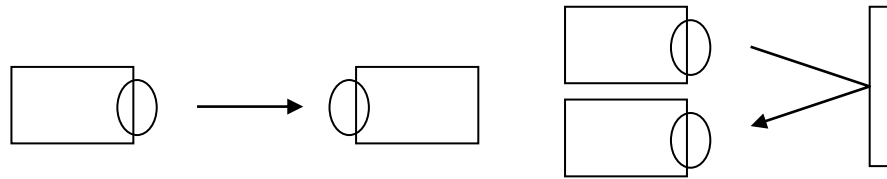
- Photoresistor
  - Small resistance at high illumination
  - Light detection



# Infrared sensors

- Intensity IR sensors

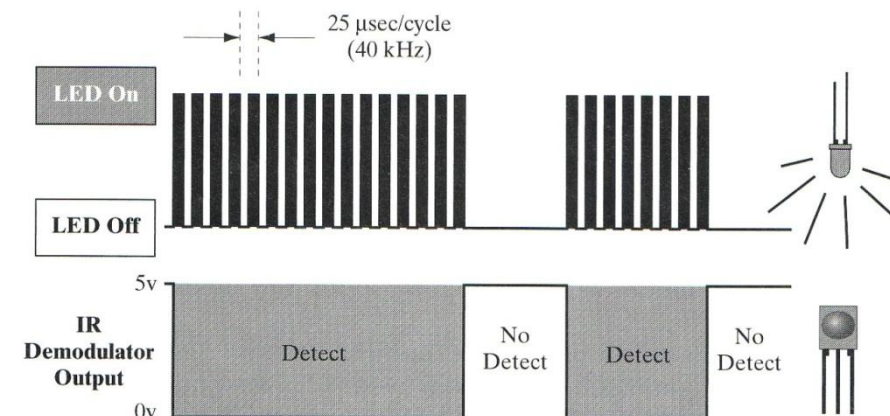
- Emit and receive IR light
- Photo-transistor



- Sensitive to daylight, reflections, distance
- Robust, cheap
- Application: object detection, optical encoder

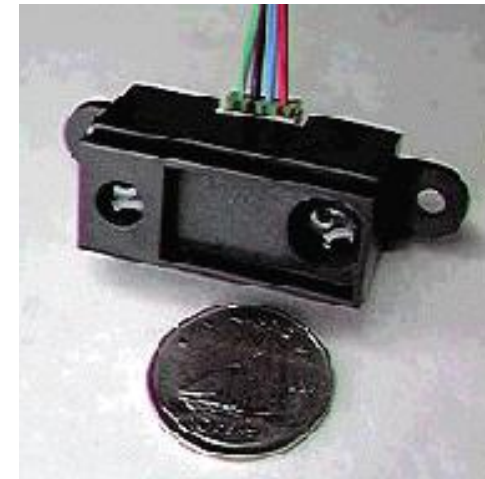
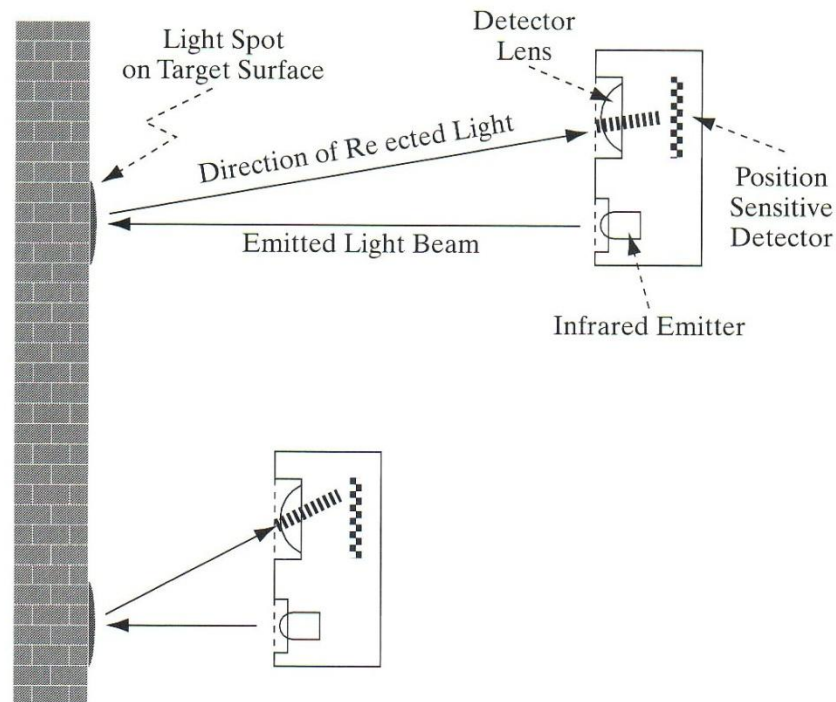
- Modulated IR sensors

- Modulation and demodulation
- Pulse detection
- More robust
- IR remotes, etc.



# Infrared sensors

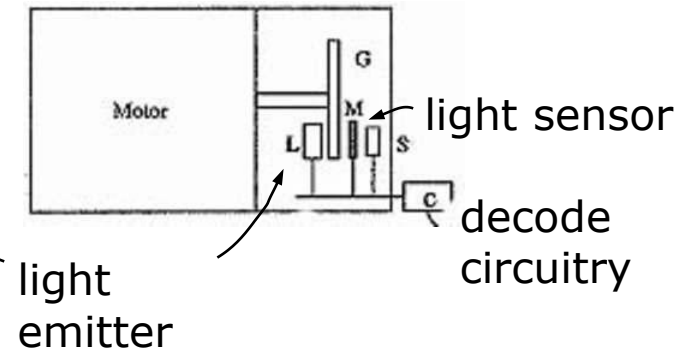
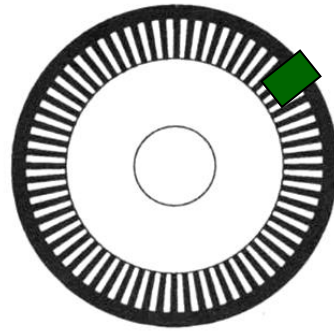
- Range sensors
- Measuring angle between the emitted and received light  
-> triangulation



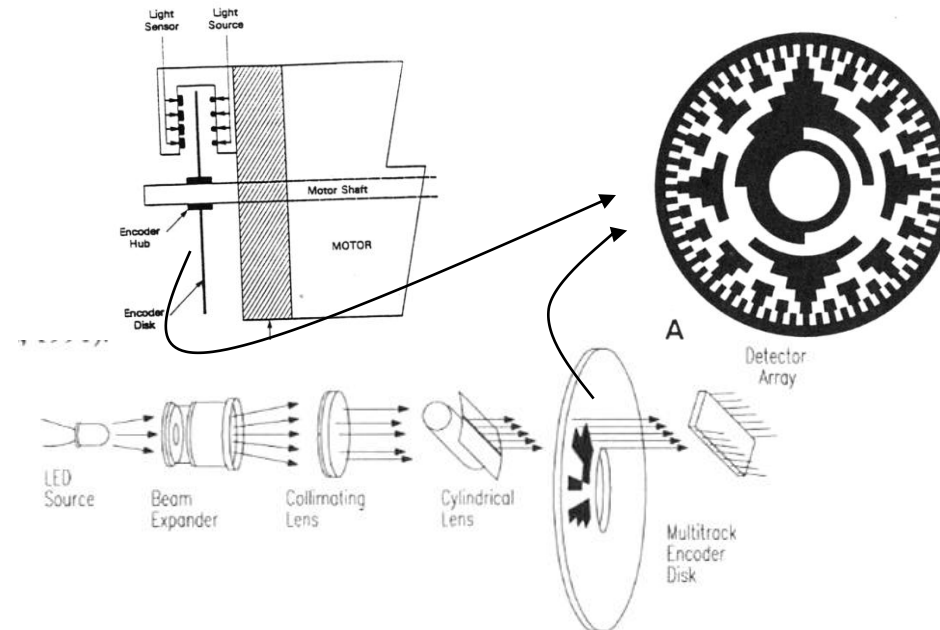
- Non-sensitive on ambient light

# Measuring rotation

- Incremental Optical Encoders
  - Relative rotation

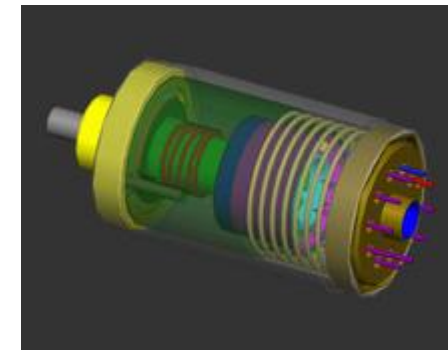


- Incremental Optical Encoders
- Absolute position
  - Gray code



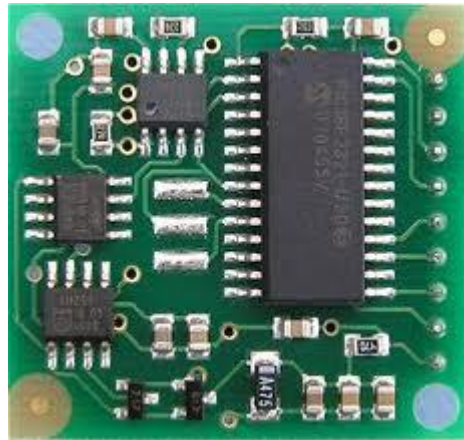
# Inertial sensors

- Gyroscope
  - Measuring change of orientation
  - based on the principles of angular momentum
- Accelerometer
  - Measures acceleration, also orientation
  - Uniaxial, triaxial
  - Vibration sensor, vibration analysis, detection of orientation
  - Nintendo Wii, smart phones



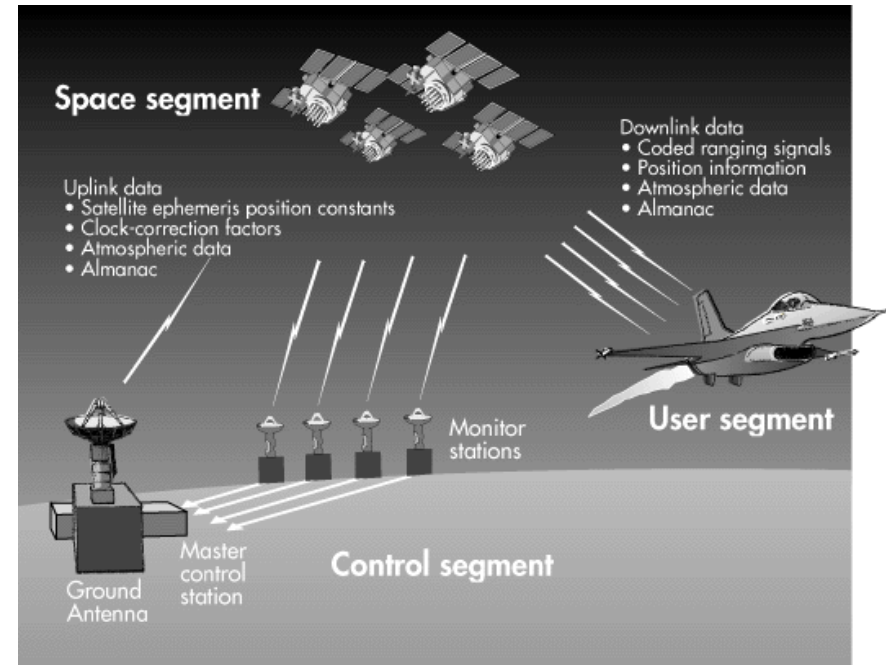
# Compass

- Electronic compass
- Absolute orientation of the robot
  - N, S, E, W



# GPS

- Global Positioning System
- 24 satellites at the height of 20200 km
- Atomic clock
- Satellite emit the time and position data
- At least 4 satellites should be visible
- Differential GPS – additional (terrestrial) signals are considered



# Tactile sensors

- Haptic technology
- Buttons, switches
- Bumpers (collision sensors)
- Touch sensors on the robot arm
- Different types:
  - Piezoresistive
  - Piezoelectric
  - Capacitive
  - Elastoresistive
- Artificial skin



# Acoustic sensors

- Perception of sound

- Sonar



- Microphone

- Array of microphones
- Detection the sound direction



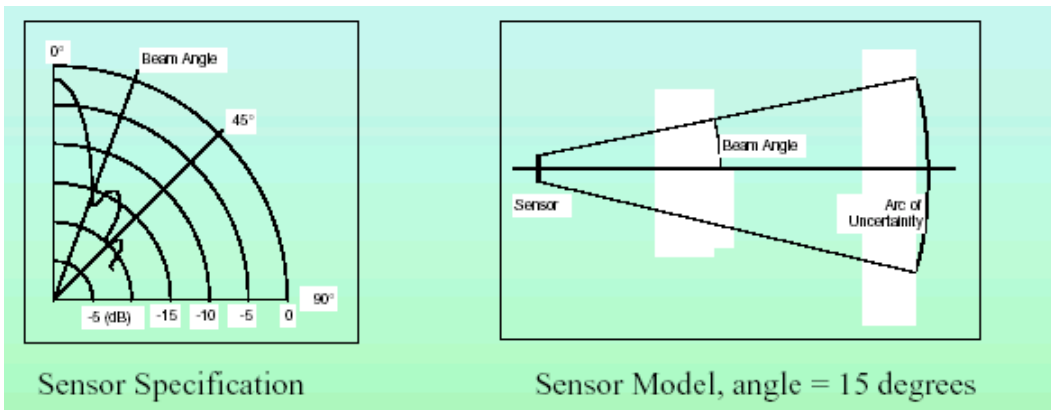
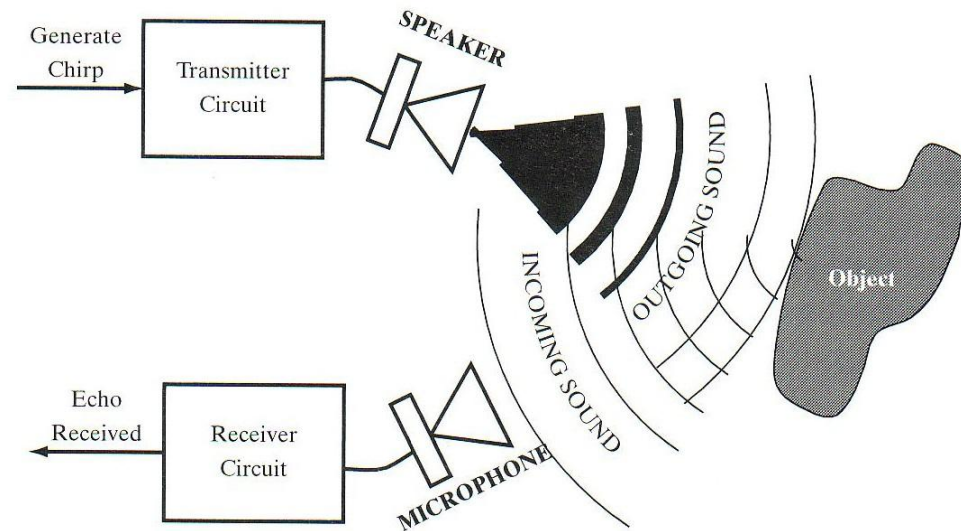
# Range sensors

---

- Stereo vision
- Shape from X
- Coded light range sensor
  
- IR range sensor
  
- Time Of Flight sensors
  - Emit the signal, wait until it is back, measure the time
  - RADAR
  - SONAR
  - LIDAR
  - ToF cameras

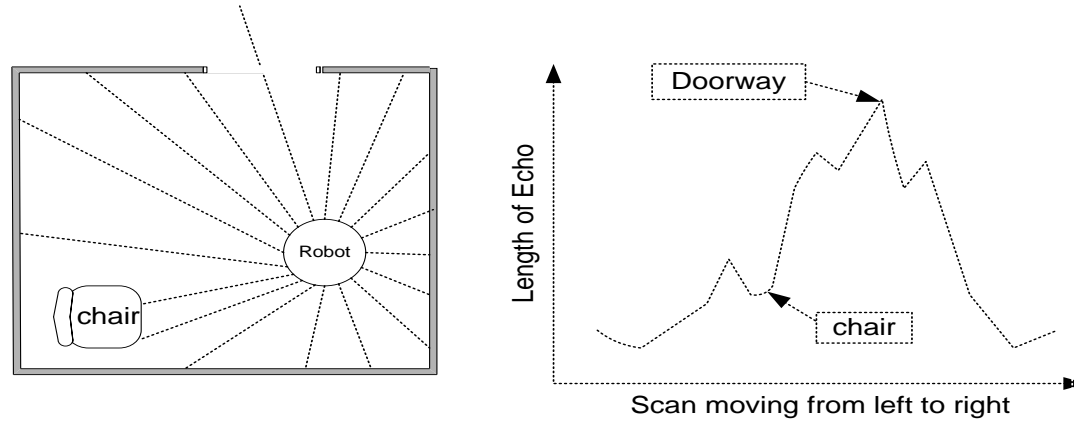
# Sonar

- Emits ultrasound
- Measure the time
- Bat, dolphin
- From a couple of cm to 30 m
- 30 degrees angular accuracy
- Quite slow:  
200ms for 30m

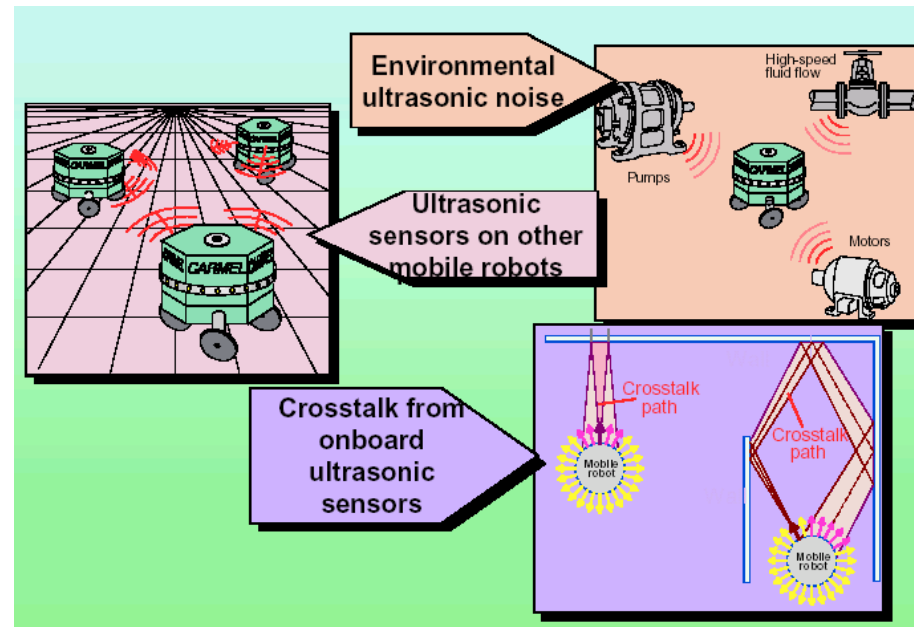


# Sonar

- Usage:  
Mapping of space

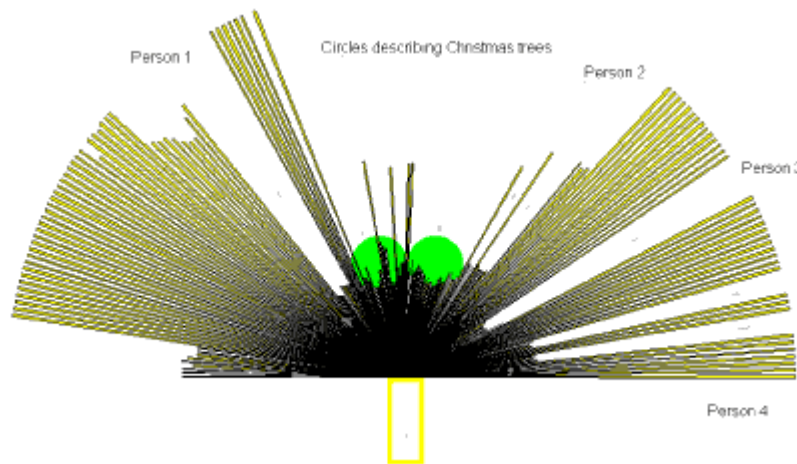
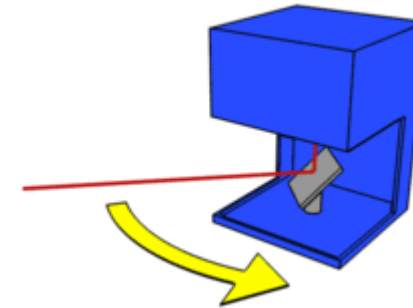


- Problem:  
noise,  
interference



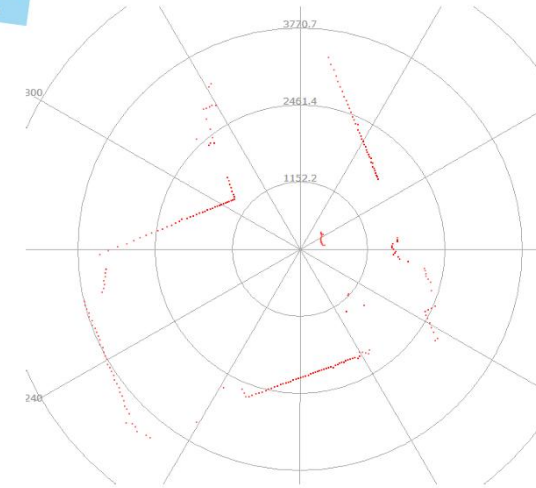
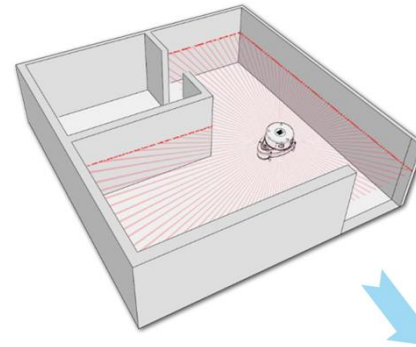
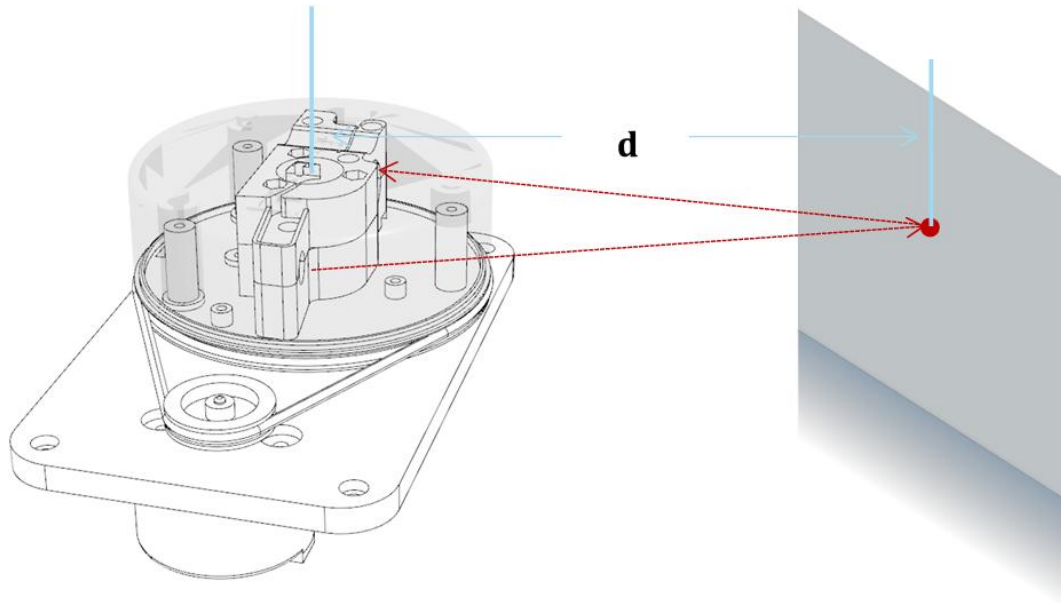
# Laser range sensors

- LIDAR (**L**ight **D**etection **A**nd **R**anging)
- Emits laser pulses
- Rotating mirror – different angles (up to 180 degrees)
- Vertical movement – the entire hemisphere
- Better angular accuracy (0.25 degrees)
- Faster
- Different ranges, indoor, outdoor
- Robust



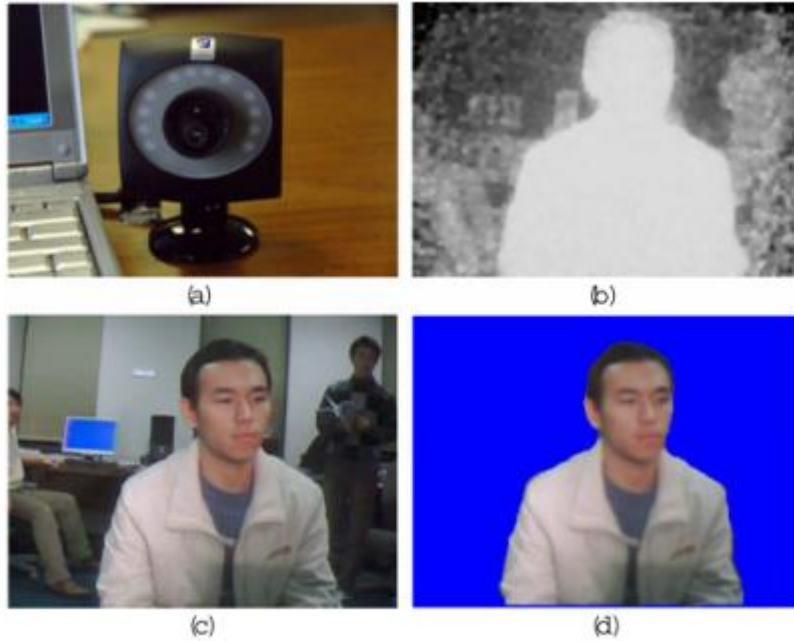
# Triangulation based LIDAR

- Low-cost LIDARs
- Based on triangulation, and not ToF



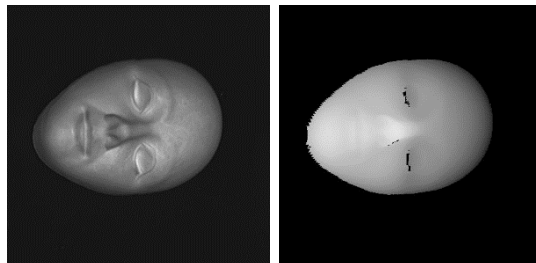
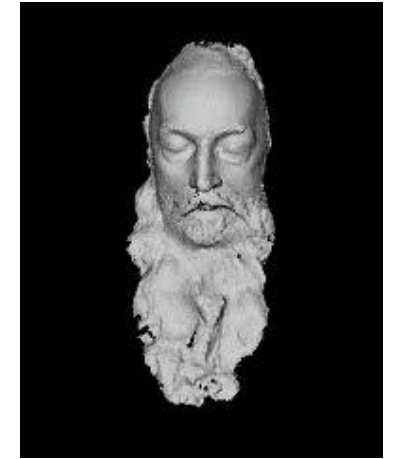
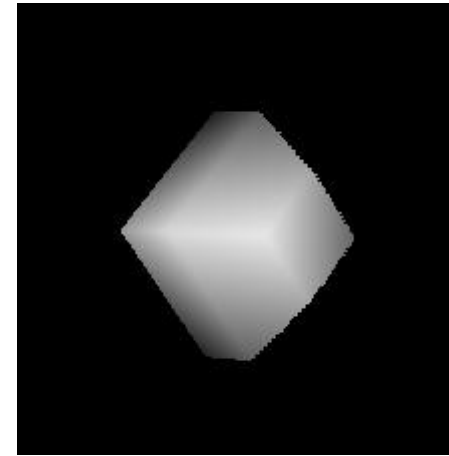
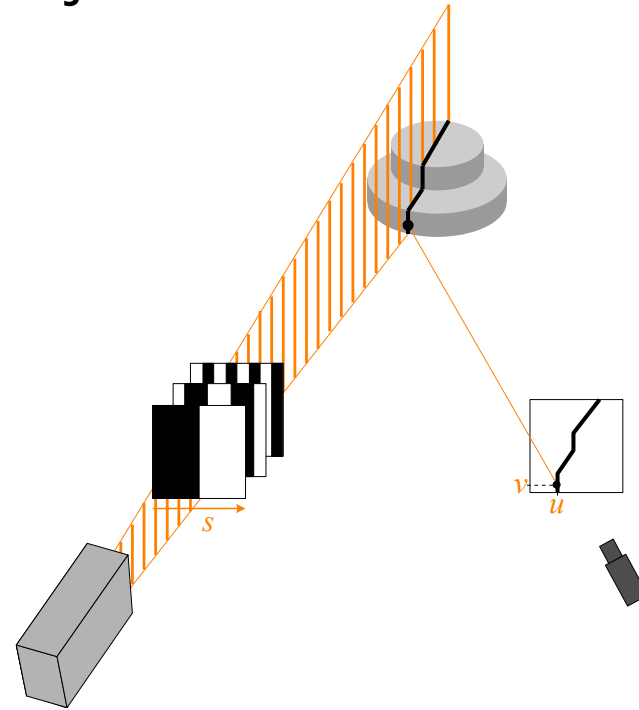
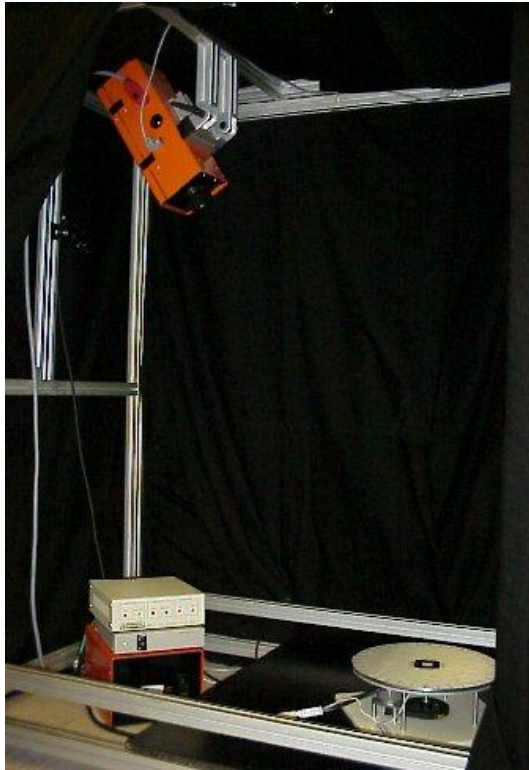
# TOF cameras

- Time-of-flight cameras
- Time of pulse travel

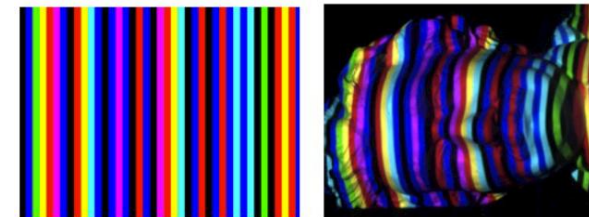


# Coded light range sensor

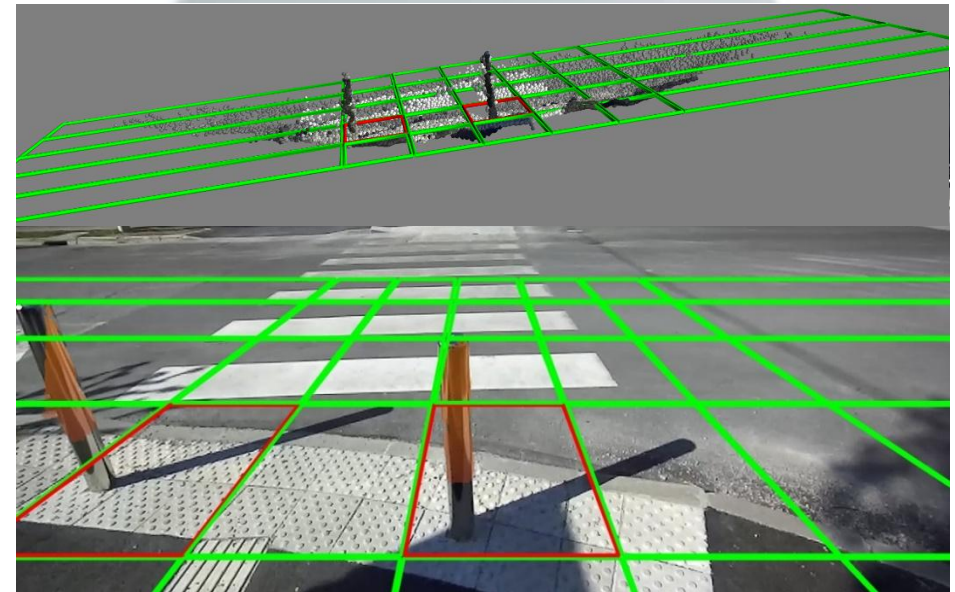
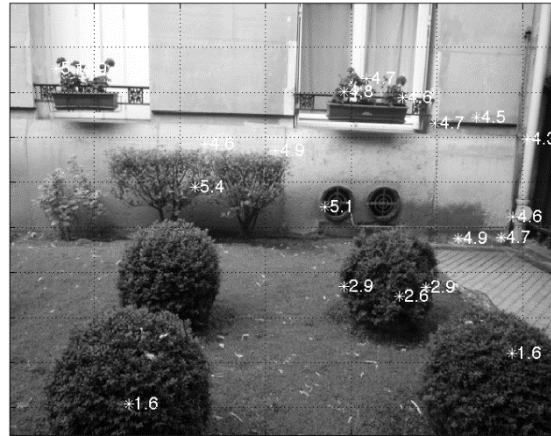
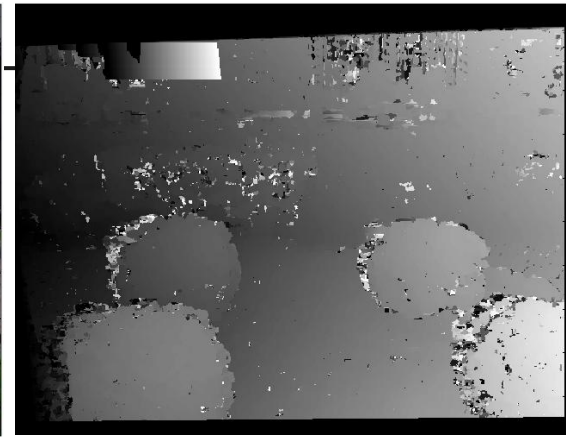
- Camera and stripe projector



Color coding:

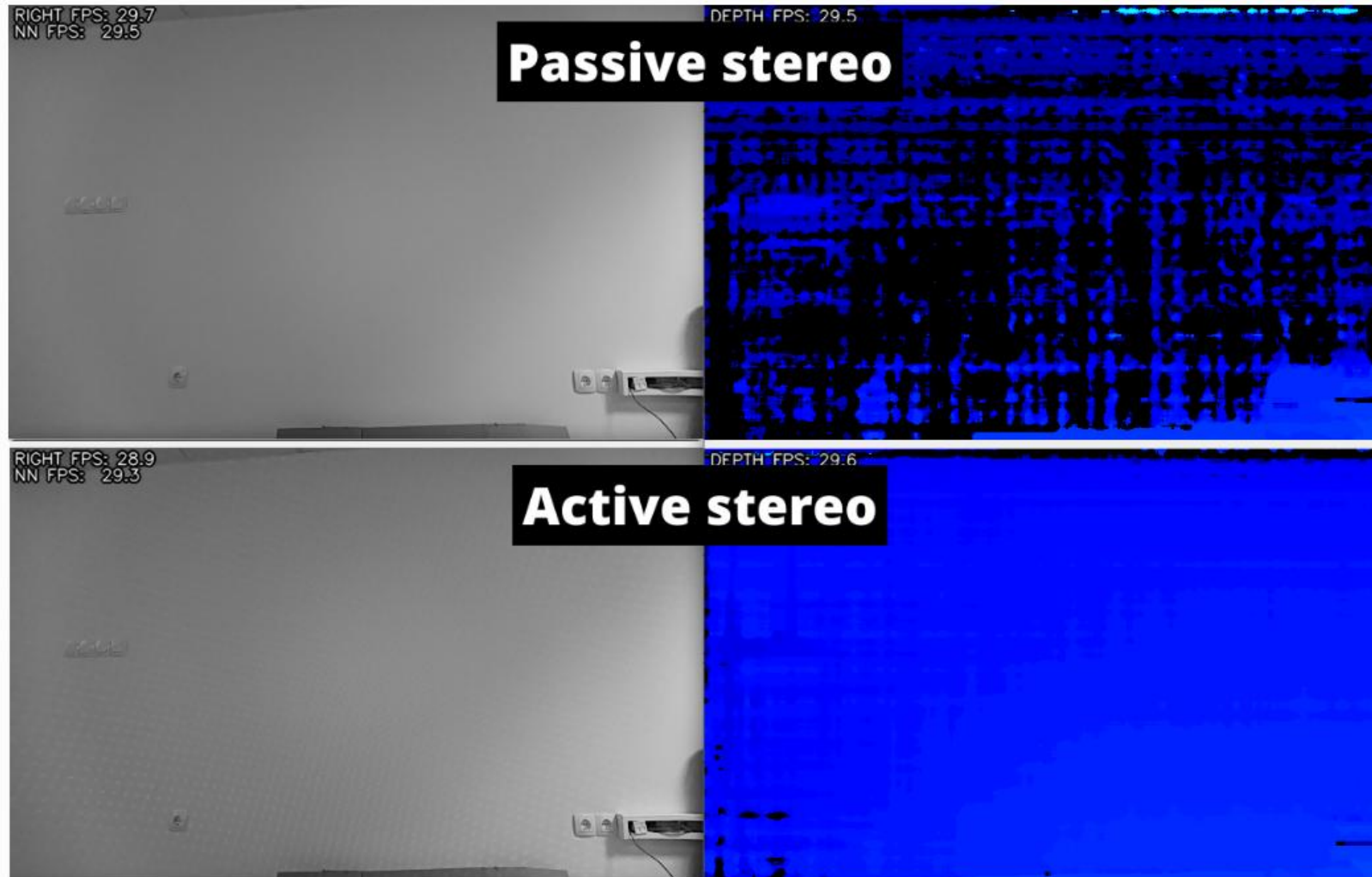


# Stereo cameras

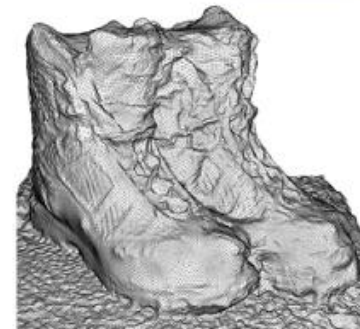
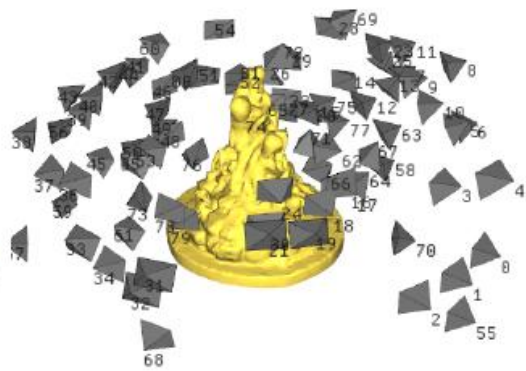
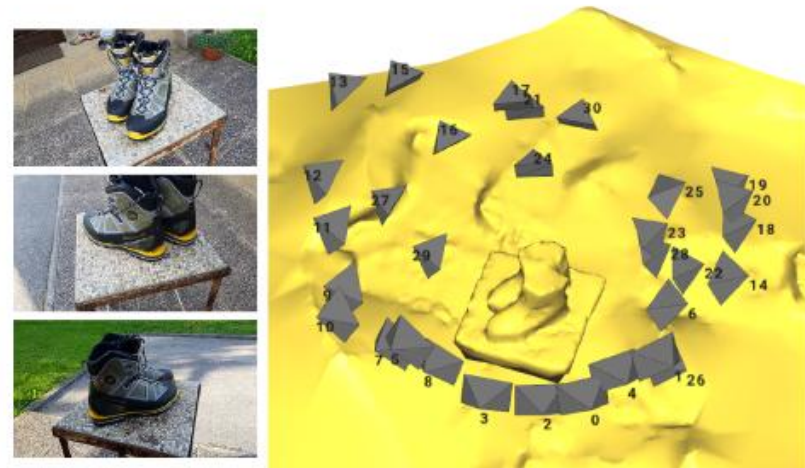
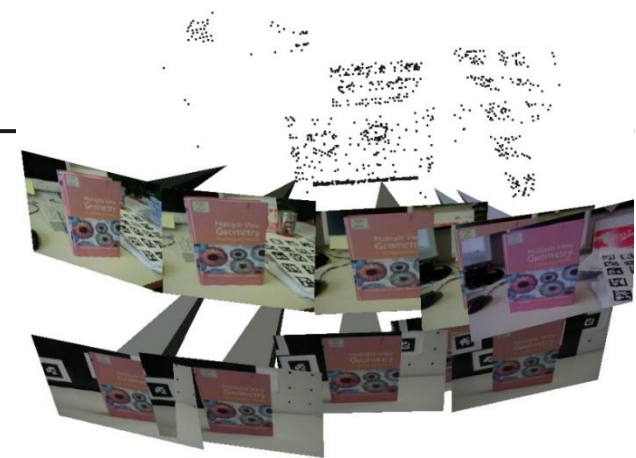
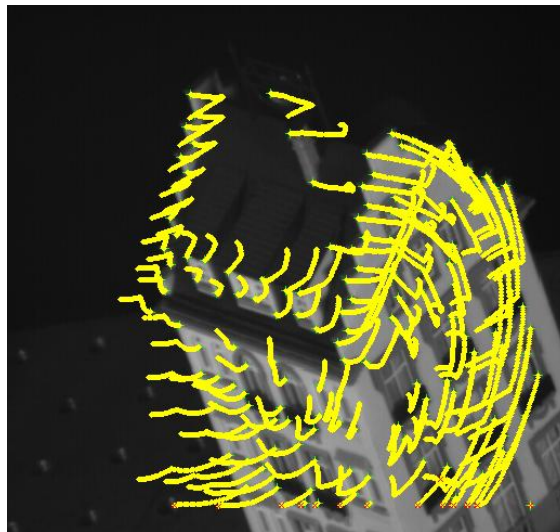


# Active stereo vision

- Actively project (an IR) pattern to increase the texture on the surfaces



# Structure from motion

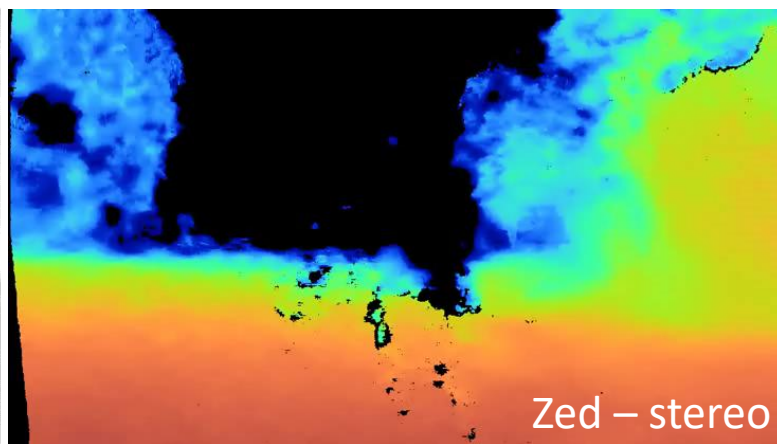
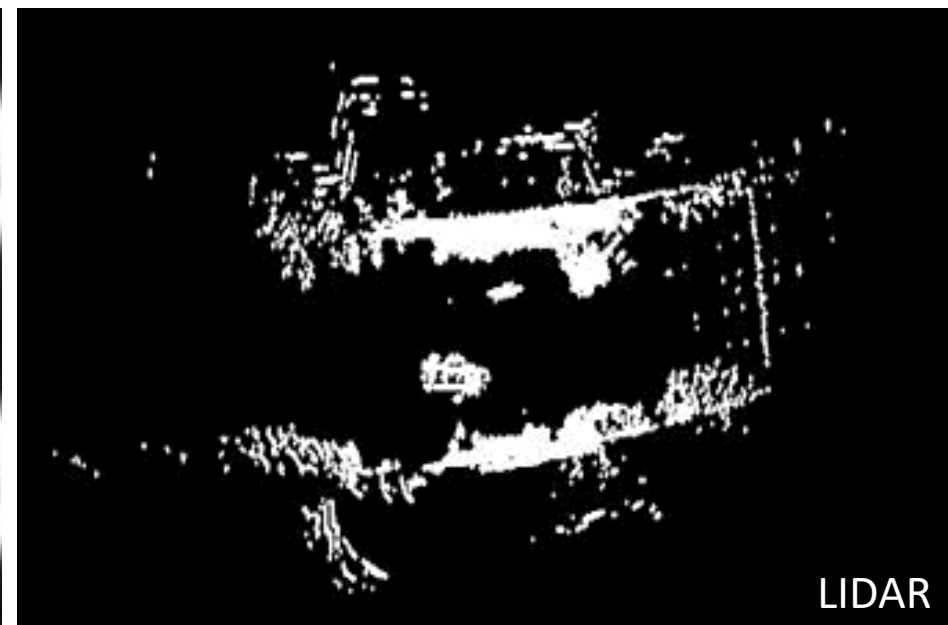


# Other sensors

---

- Exteroceptive sensors
  - Wind speed
  - Temperature
  - Humidity
- Proprioceptive sensors
  - Battery level
  - Temperature of CPU, motors, sensors, etc.

# Multimodal perception



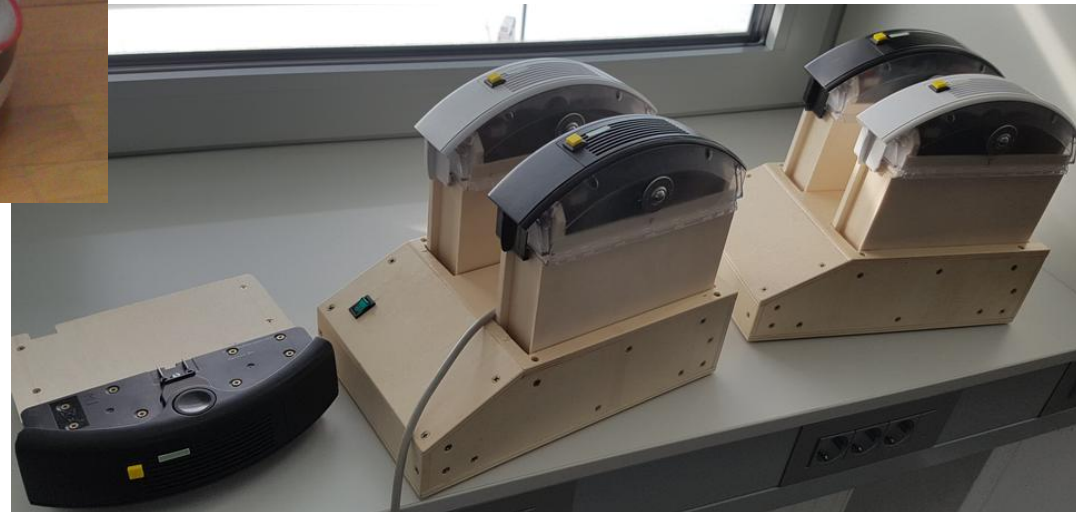
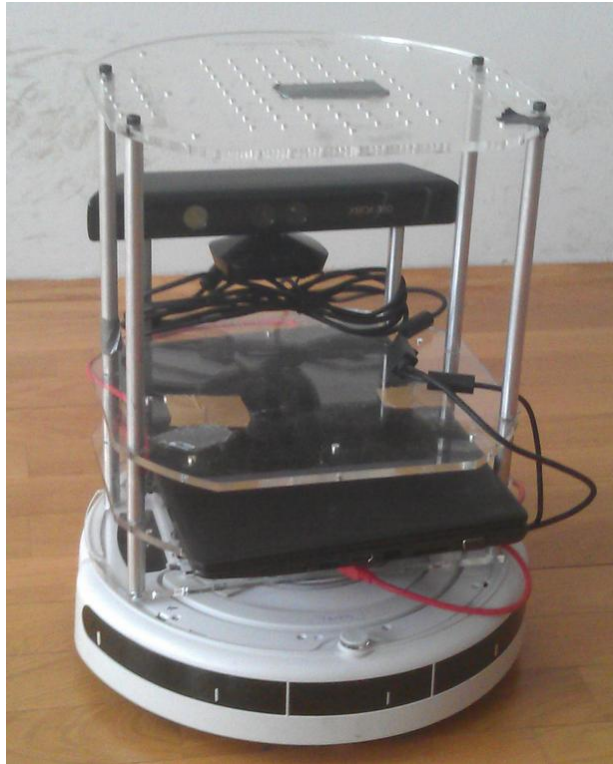
UL FE, FRI, Janez Perš, Matej Kristan

# Sensor fusion

---

- One sensor often does not suffice
  - Noise
  - Limited accuracy
  - Non-reliability
  - Limited sensing range
- => Fuse the results of several sensors
- Sensor fusion: fusion on the level of sensors
  - Combine signals in one data structure on a low level
- Sensor integration: Fusion on the level of representations
  - Process data from every sensor independently and merge the obtained information on a higher level
- Fusion of data from multiple sources:
  - Measurement from different sensors
  - Measurement from different times
  - Measurement from different locations

# TurtleBot++



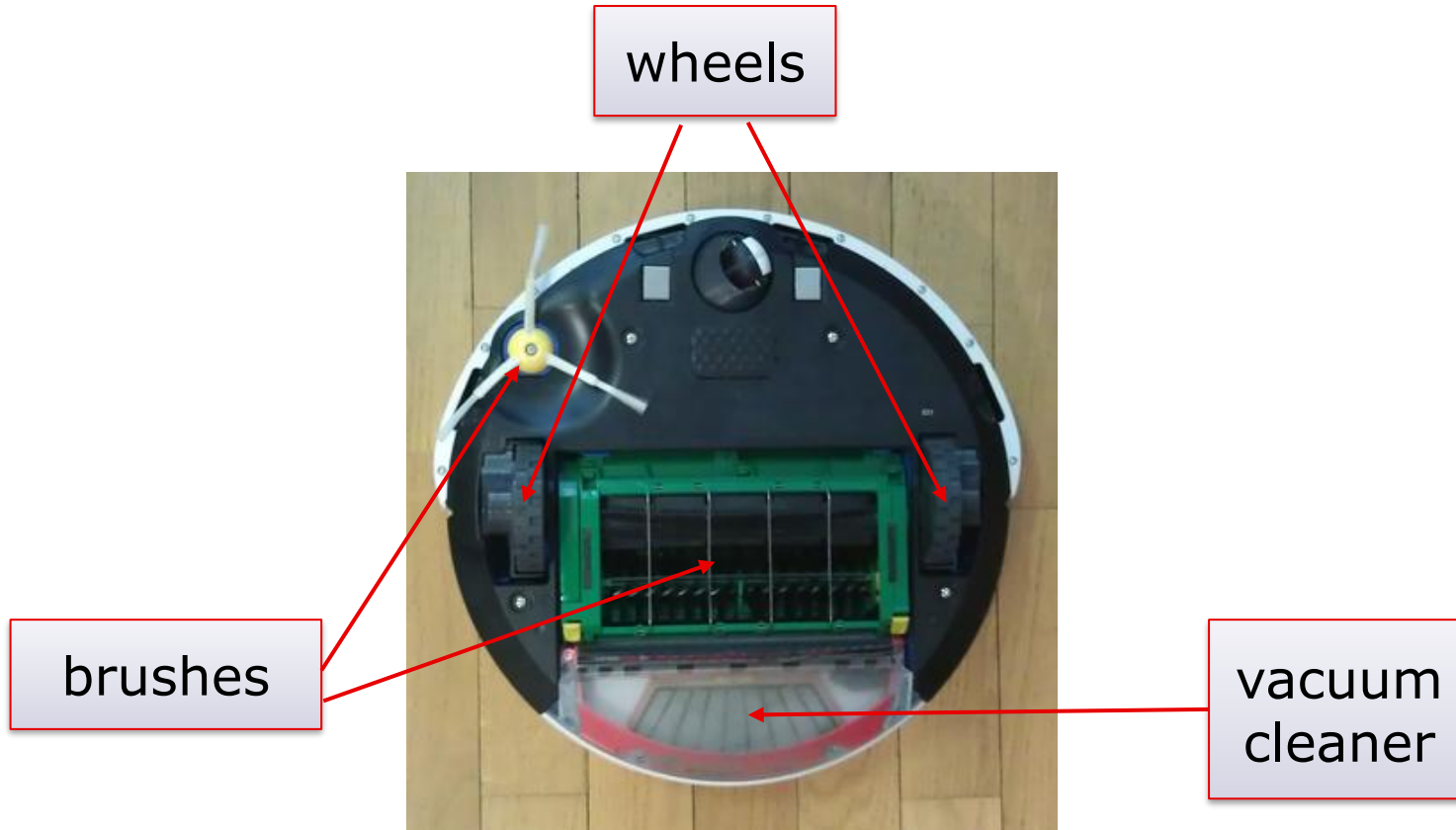
# iRobot Roomba

- Actuators and sensors



# Motors

- Changeable speed of the wheels
  - pulse-width modulation (PWM)



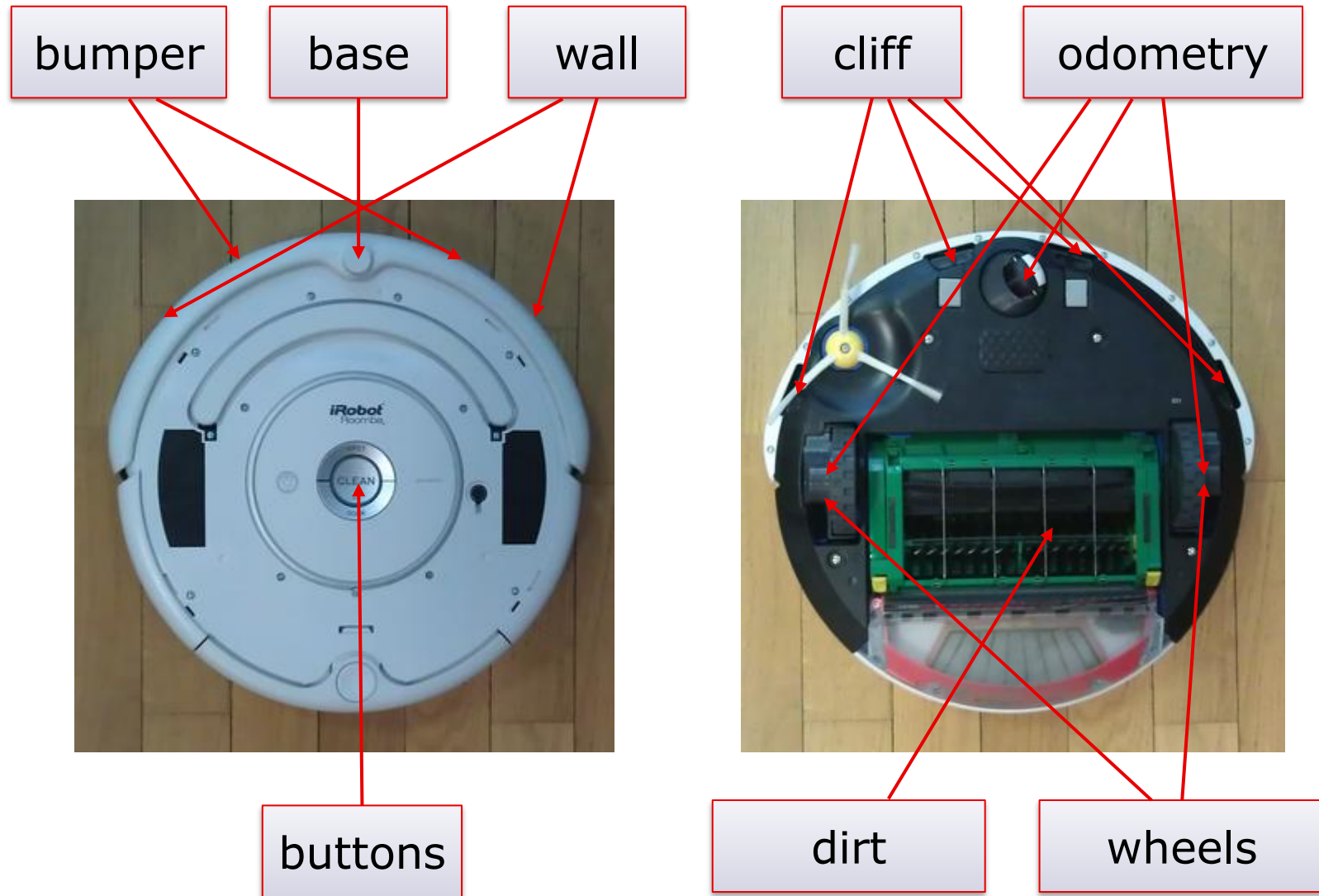
- On/off motors for brushes and vacuum cleaner

# Wheels

- Differential control system
  - Two independently controlled wheels
- Electric motor
  - high speed
- 25:1 reduction
  - large torque

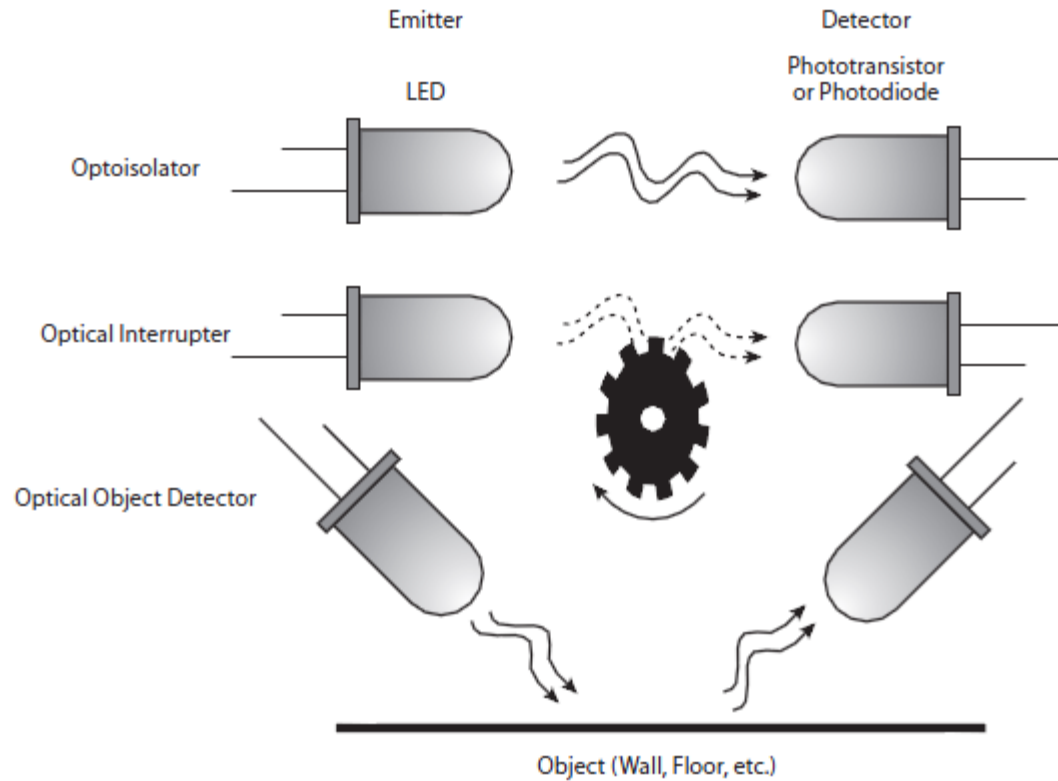


# Sensors



# IR sensors

- IR sensors



base

bumper

odometry

wall

cliff

- Micro switches:

buttons

wheels

- Capacitive sensor:

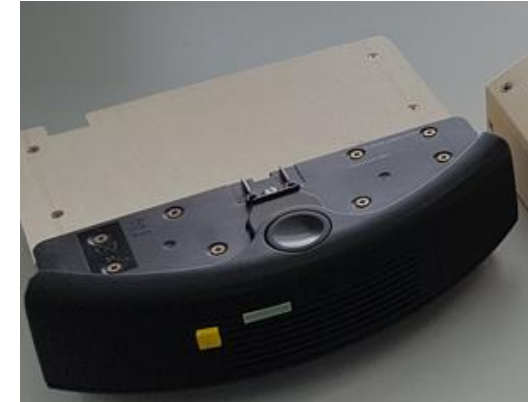
dirt

# Power supply

- Measuring power supply
  - capacitance of the accumulator [mAh]
  - voltage [V]
  - current [A]
  - temperature

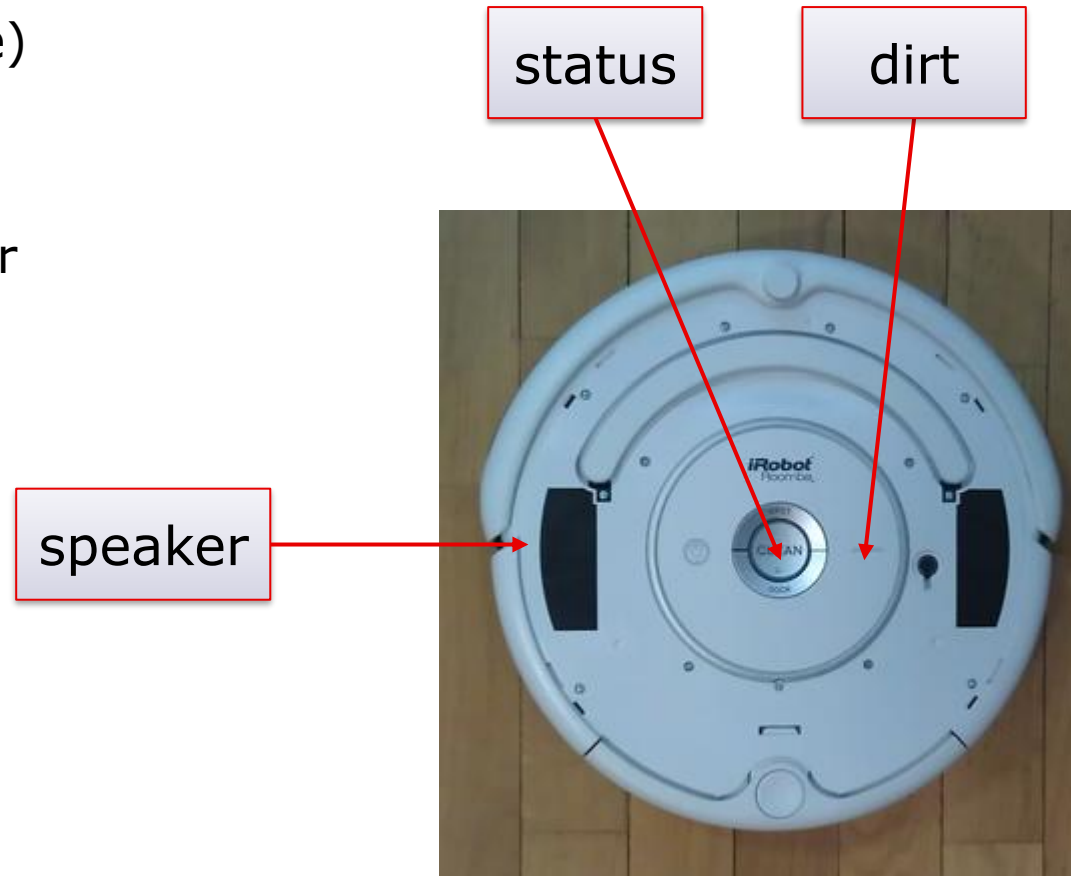


connectors



# Indicators

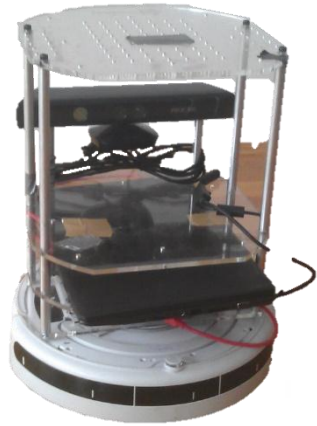
- Led lights
  - Status (green, red)
  - Dirt detection (blue)
- Speaker
  - piezoelectric beeper



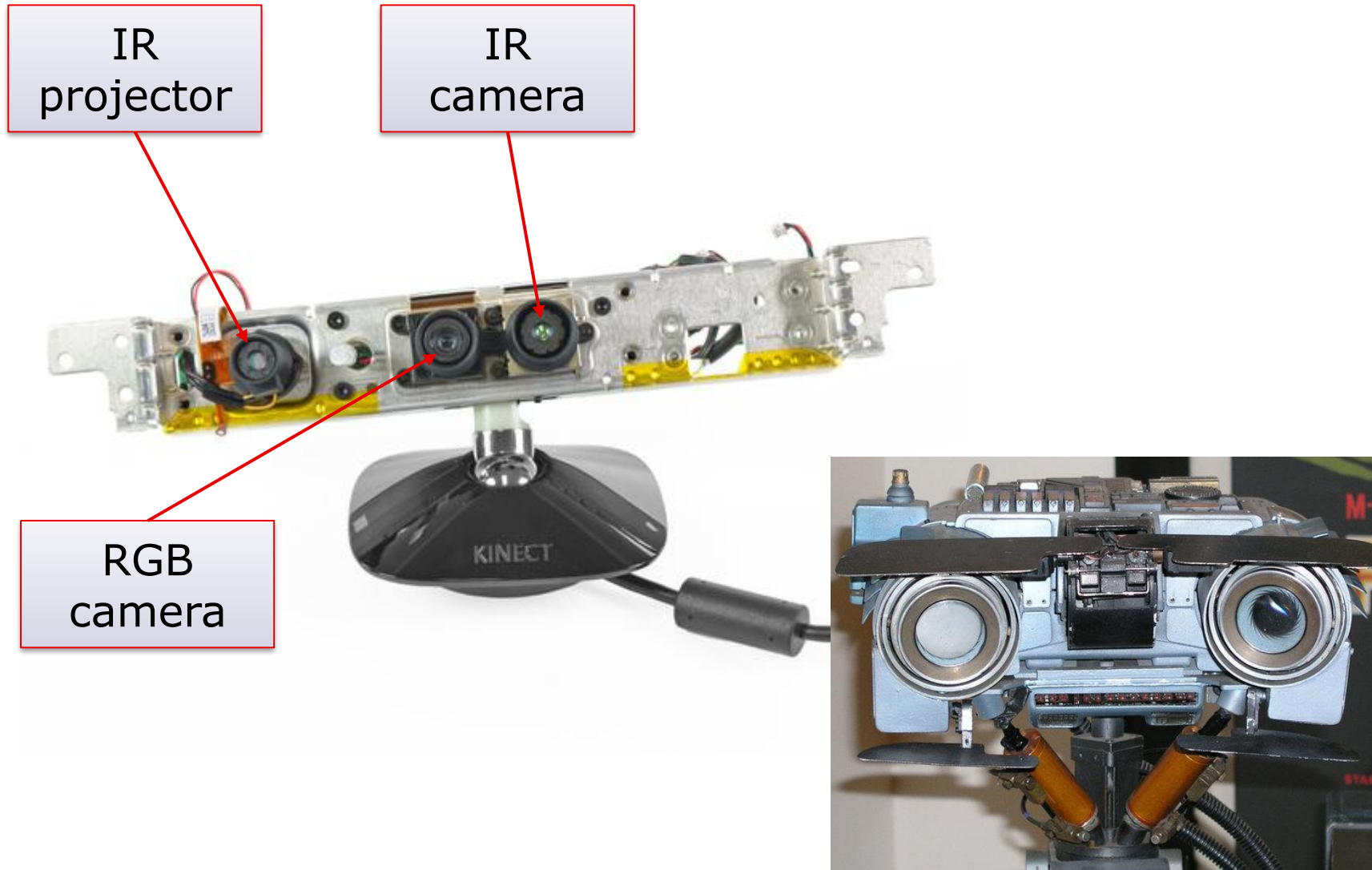
# RGBD sensor Kinect

---

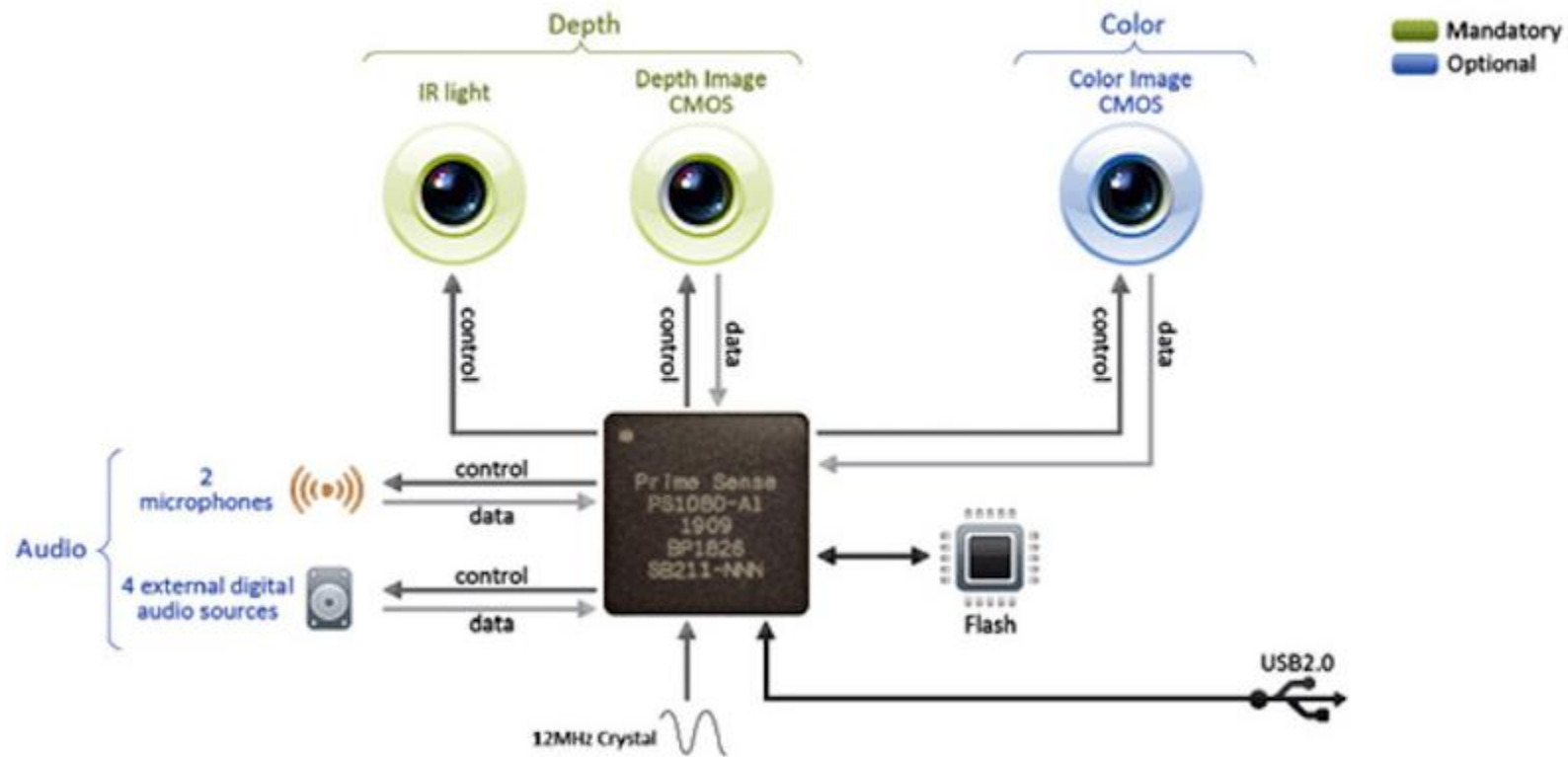
- PrimeSense sensor



# Components

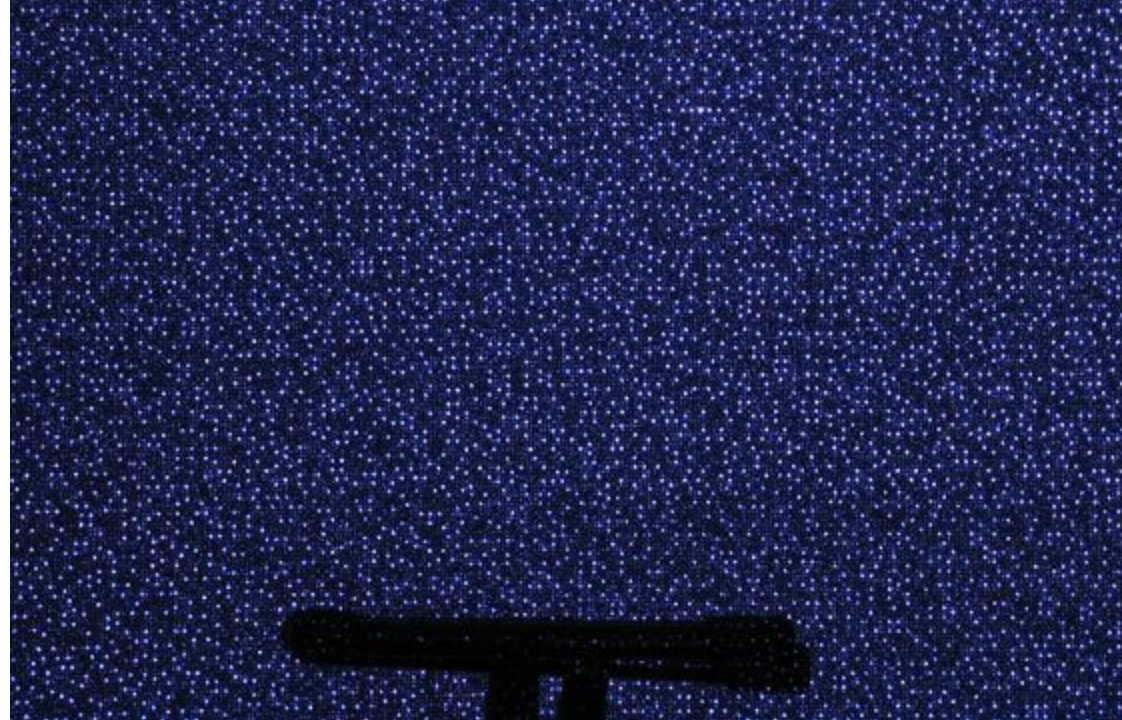


# Scheme



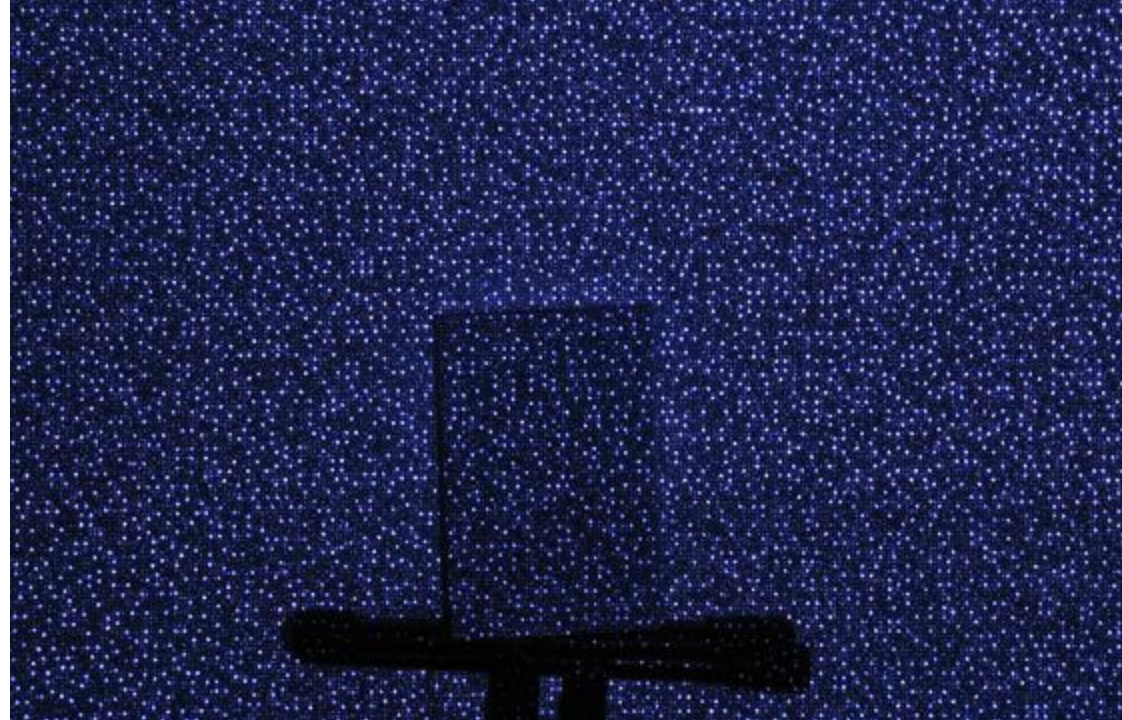
# Projected pattern

---



# Projected pattern

---



**Patent No.: US 7,433,024 B2**

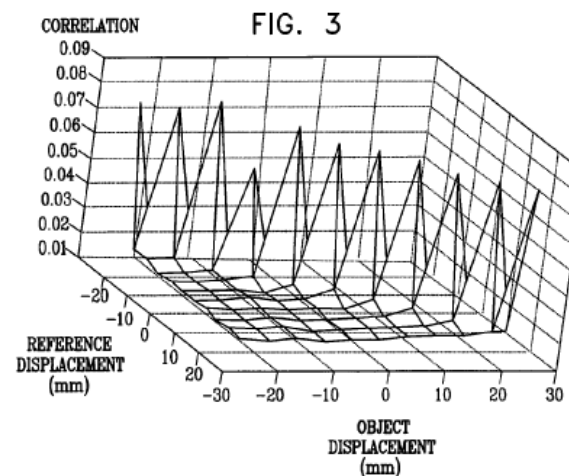
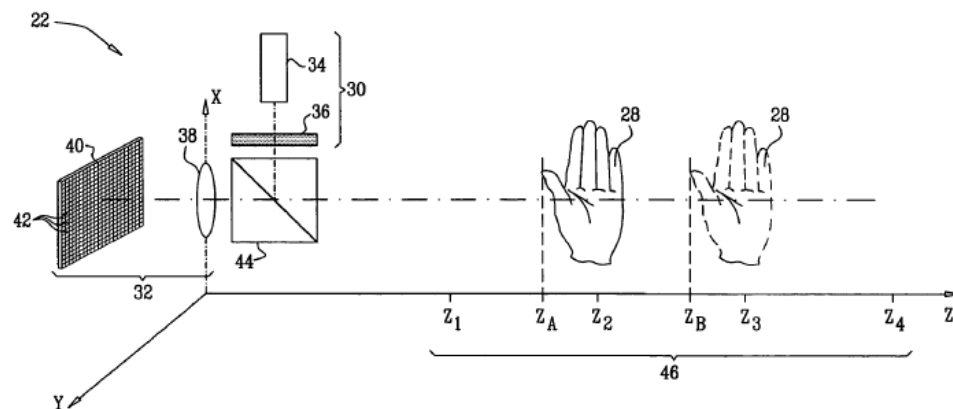
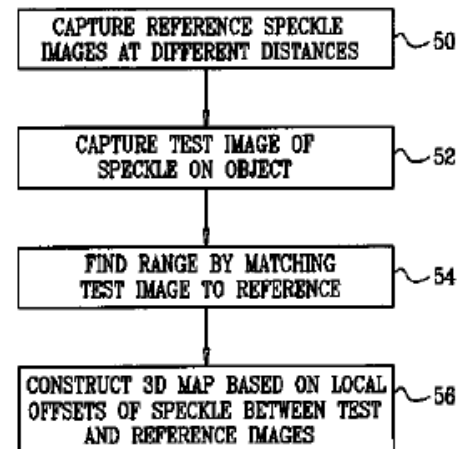
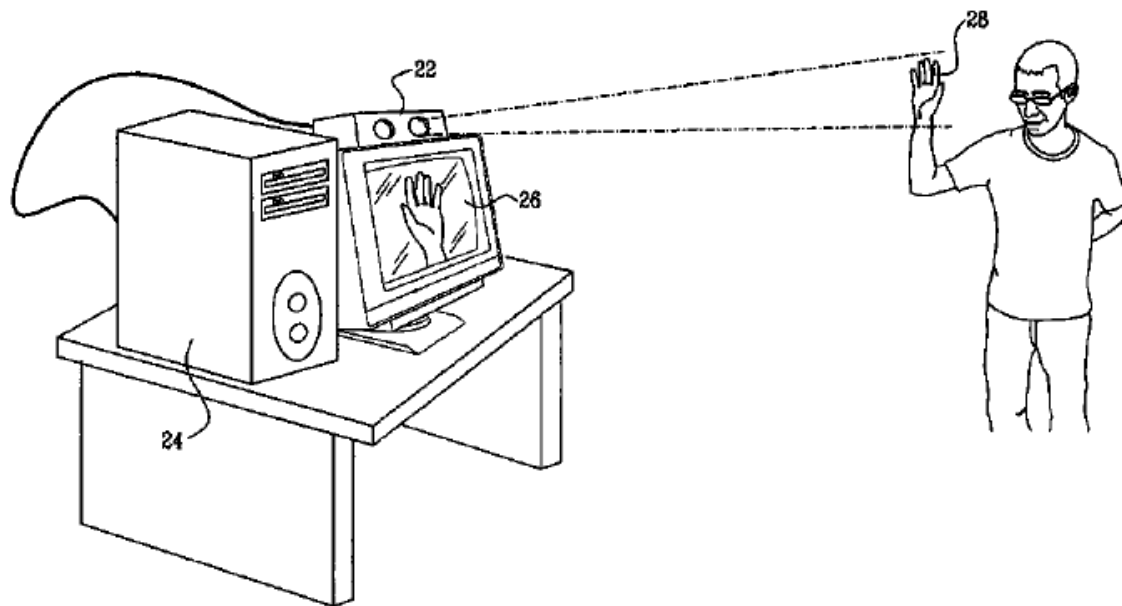
**RANGE MAPPING USING SPECKLE  
DECORRELATION**

(57)

**ABSTRACT**

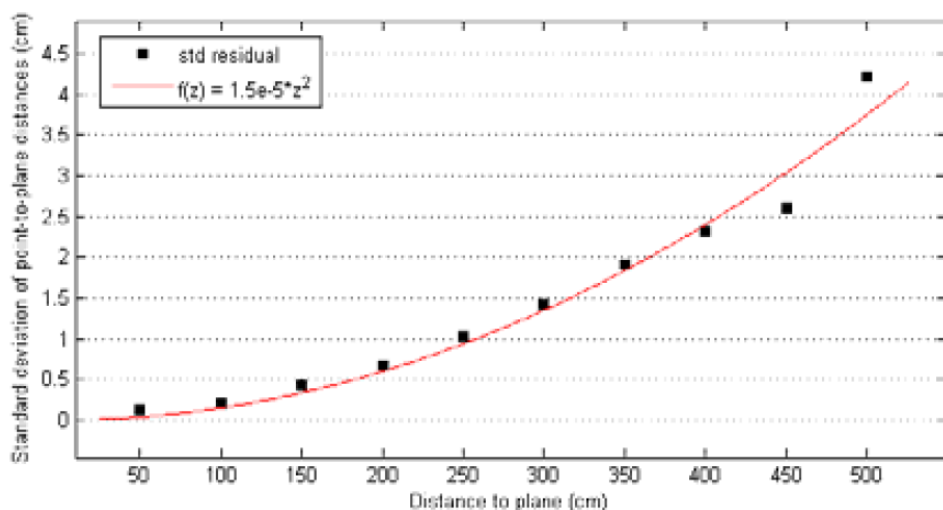
A method for mapping includes projecting a primary speckle pattern from an illumination assembly into a target region. A plurality of reference images of the primary speckle pattern are captured at different, respective distances from the illumination assembly in the target region. A test image of the primary speckle pattern that is projected onto a surface of an object in the target region is captured and compared to the reference images so as to identify a reference image in which the primary speckle pattern most closely matches the primary speckle pattern in the test image. The location of the object is estimated based on a distance of the identified reference image from the illumination assembly.

# Patent

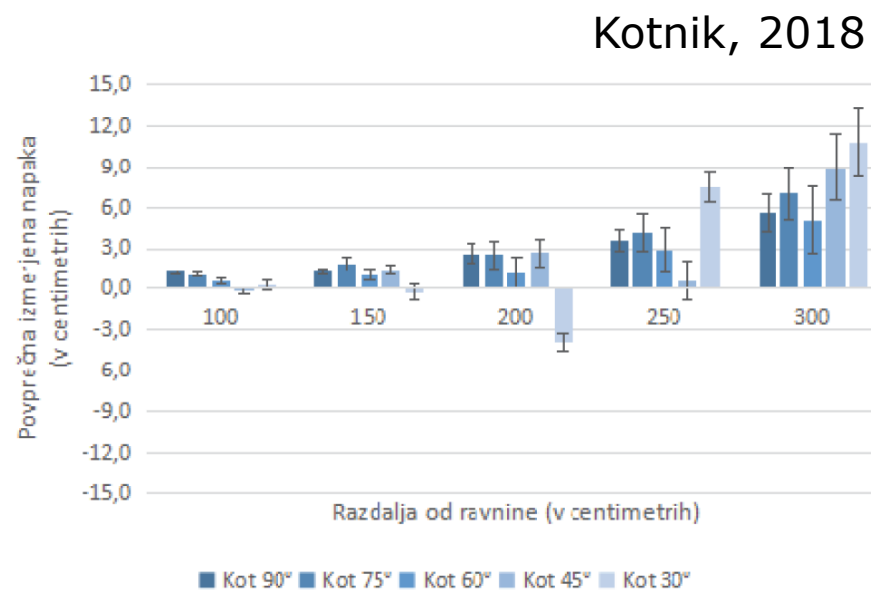


# Kinect performance

- Specifications:
  - Horizontal field of view: 57 degrees
  - Vertical field of view: 43 degrees
  - Physical tilt range:  $\pm 27$  degrees
  - Depth sensor range: 1.2m - 3.5m
  - 320x240 16-bit depth @ 30 frames/sec
  - 640x480 32-bit colour @ 30 frames/sec
  - 16-bit audio @ 16 kHz



Khoshelham, 2011



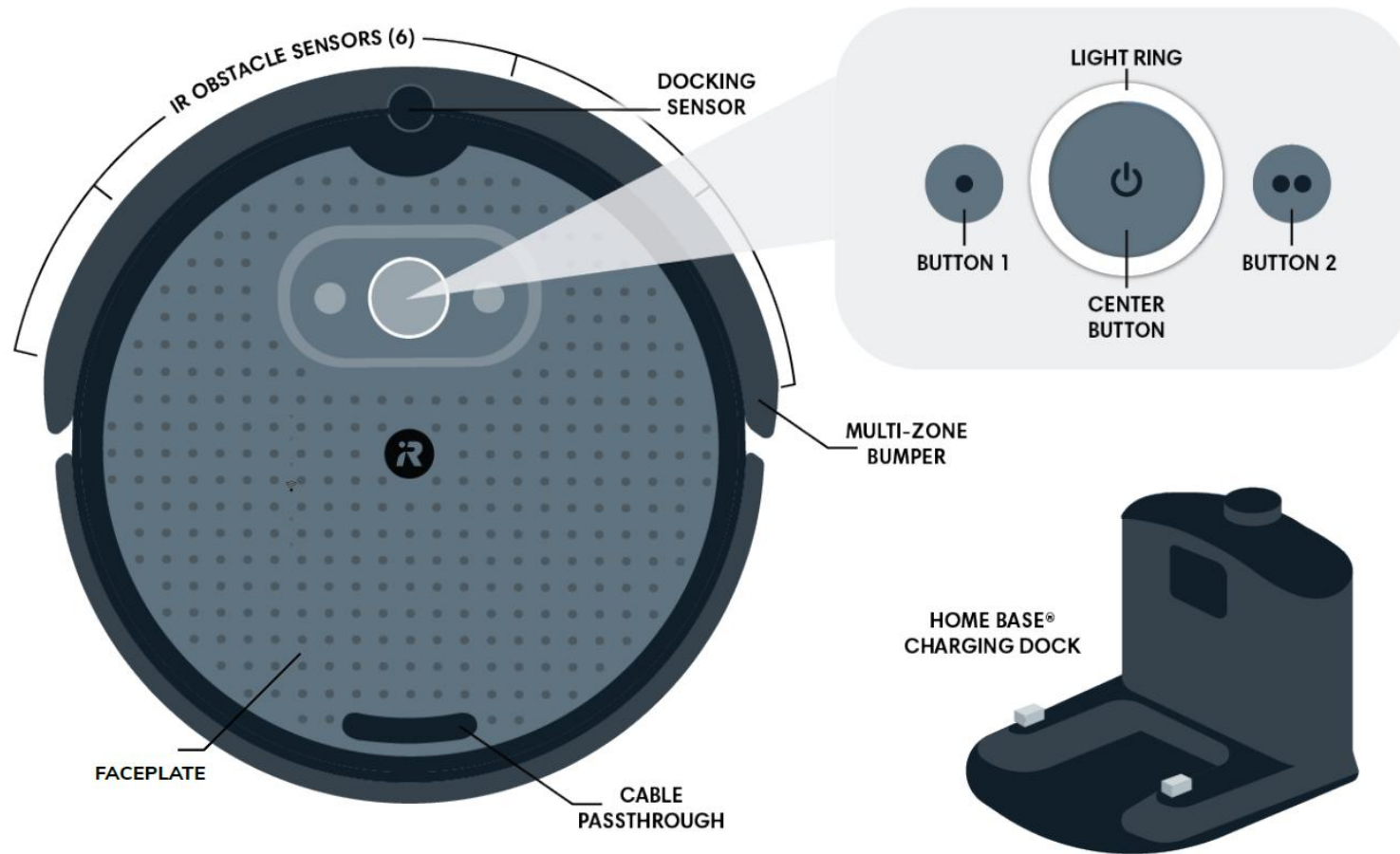
# TurtleBot 4



<b>Dimensions</b>	341 x 339 x 351 mm
<b>Weight</b>	3.9 kg
<b>Max. Speed</b>	0.31 m/s
<b>Max. Payload</b>	9 kg - Default 15 kg - Custom Configuration
<b>Operating Time</b>	2.5 - 4.0 hrs (load dependent)
<b>Camera</b>	OAK-D-PRO
<b>LiDAR</b>	RPLIDAR-A1
<b>Accessible Power &amp; USB Ports</b>	Yes
<b>OLED Display</b>	Yes
<b>Mounting Plate</b>	Yes
<b>Software</b>	ROS 2
<b>Computer</b>	Raspberry Pi 4B (4 GB)

# TurtleBot 4 Base

- iRobot Create 3



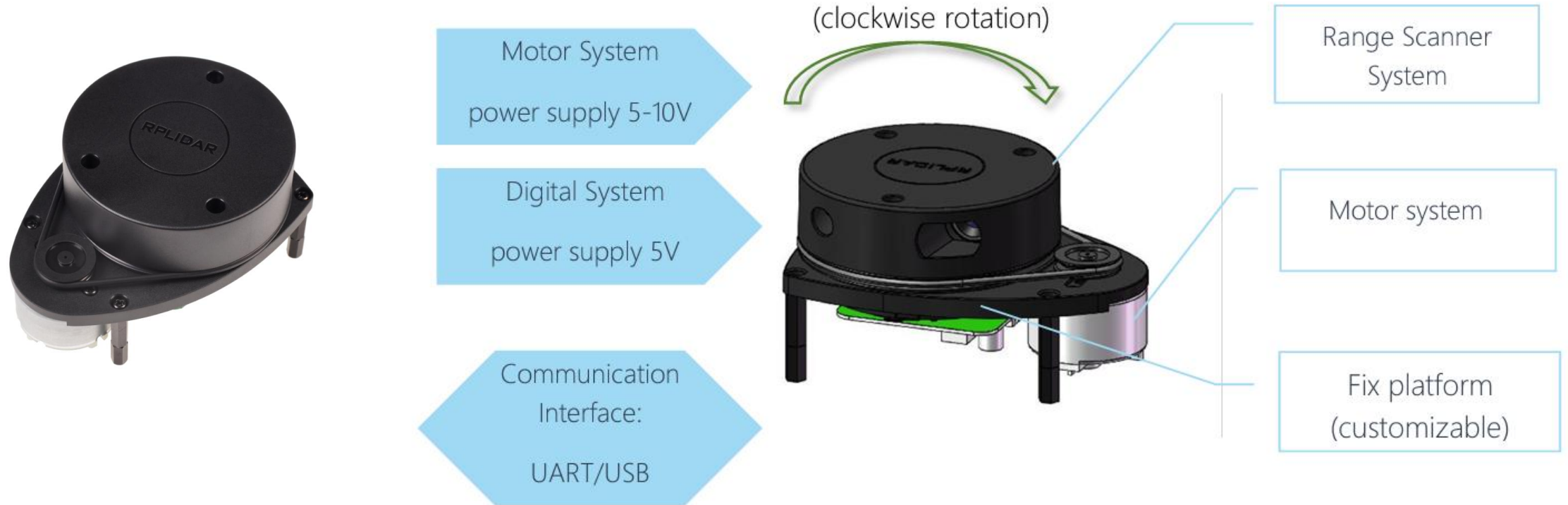
# TurtleBot 4 computer

- Raspberry Pi 4B
- 4 USB 3.0 ports
- UI Board
- 128x64 user display



# TurtleBot LIDAR

- RPLIDA A1M8
- 360° Laser Range Scanner
- 12m range
- Triangulation-based LIDAR



# TurtleBot LIDAR

Item	Unit	Min	Typical	Max	Comments
Distance Range	Meter(m)	TBD	0.15-12	TBD	White objects
Angular Range	Degree	n/a	0-360	n/a	
Scan Field Flatness	Degree	-1.5		1.5	
Distance Resolution	mm	n/a	<0.5 <1% of the distance	n/a	<1.5 meters All distance range*
Angular Resolution	Degree	n/a	≤1	n/a	5.5Hz scan rate
Sample Duration	Millisecond(ms)	n/a	0.125	n/a	
Sample Frequency	Hz	n/a	≥8000	8010	
Scan Rate	Hz	1	5.5	10	Typical value is measured when RPLIDAR A1 takes 360 samples per scan

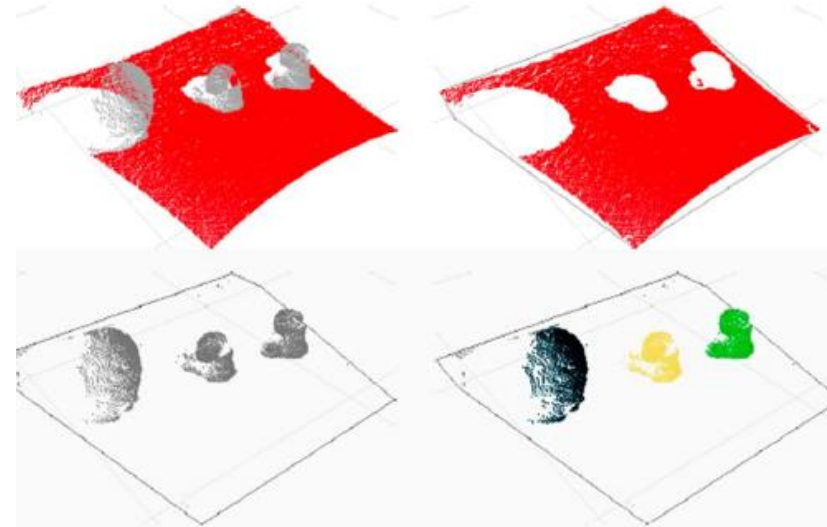
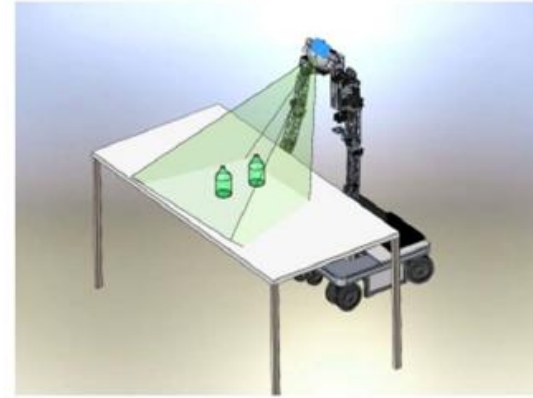
# TurtleBot RGBD camera

- Luxonis OAK-D-Pro
- Active stereo vision
  - IR laser dot projection
- IR illumination LED
  - For night vision
- RVC2
  - Robotics Vision Core 2
  - Performanc SoC
  - CV methods...

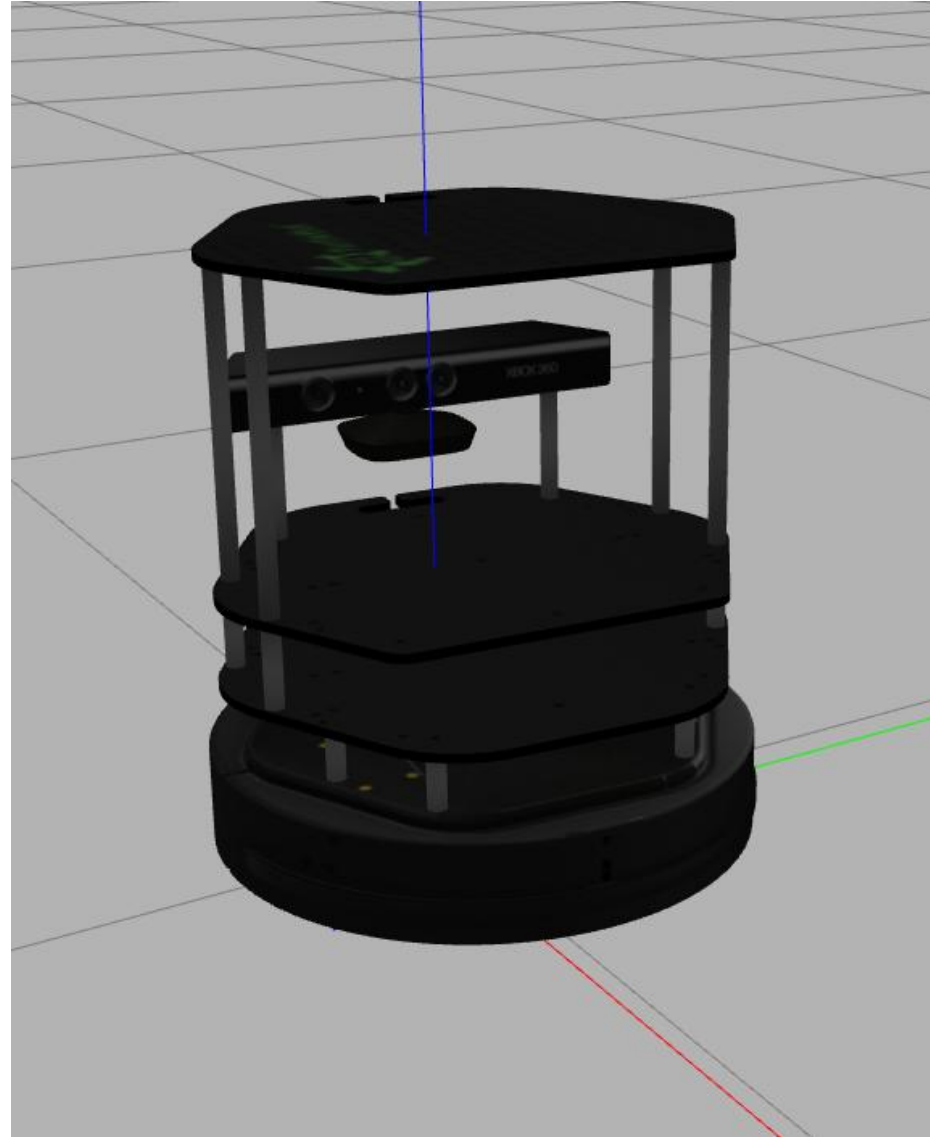


Camera Specs	Color camera	Stereo pair
Sensor	OV9782 (PY074)	OV9282 (PY044)
DFOV / HFOV / VFOV	89° / 80° / 55°	89° / 80° / 55°
Resolution	1MP (1280x800)	1MP (1280x800)
Focus	FF: 19.6cm - ∞	FF: 19.6cm - ∞
Max Framerate	120 FPS	120 FPS
F-number	2.0 ±5%	2.0 ±5%
Lens size	1/4 inch	1/4 inch
Effective Focal Length	2.35mm	2.35mm
Pixel size	3µm x 3µm	3µm x 3µm

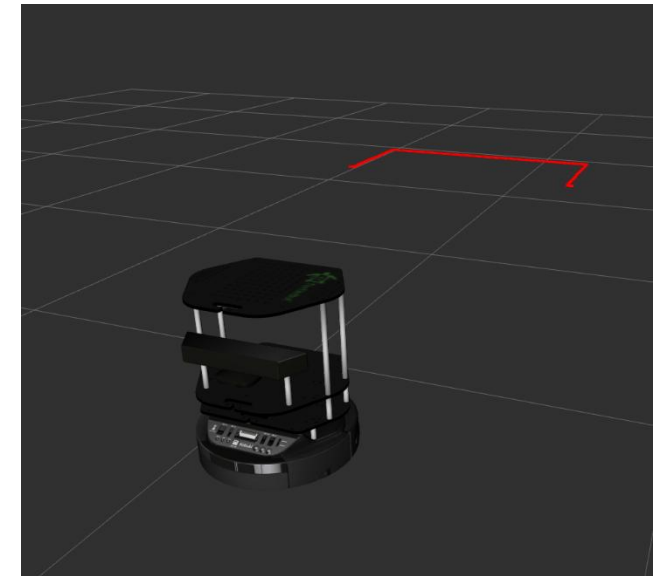
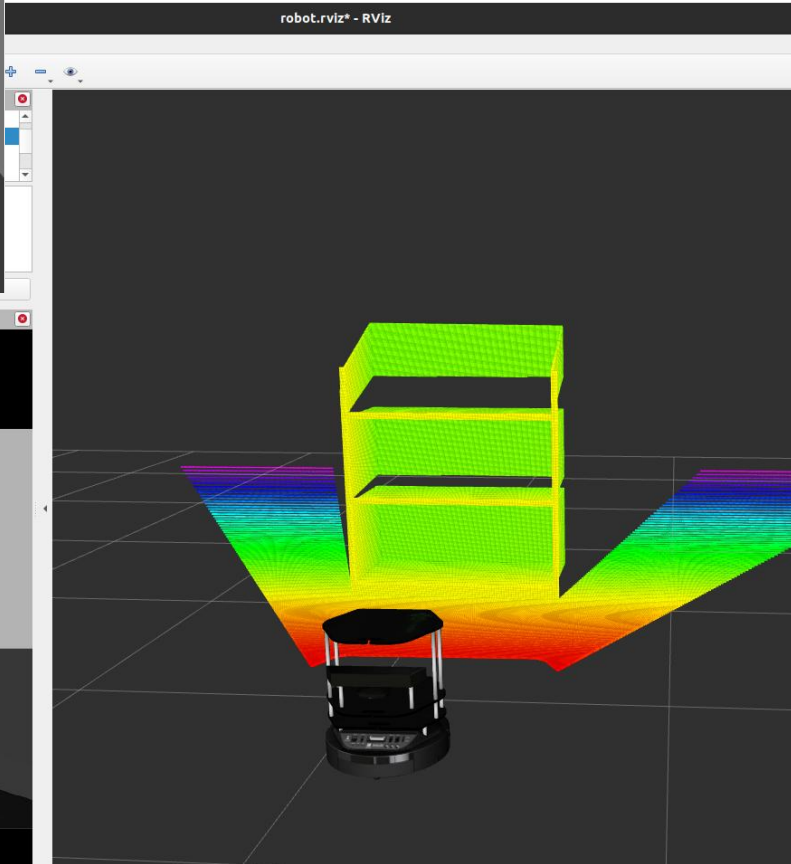
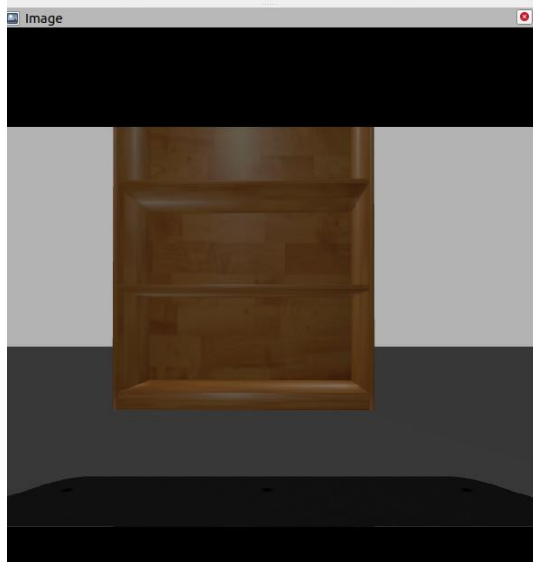
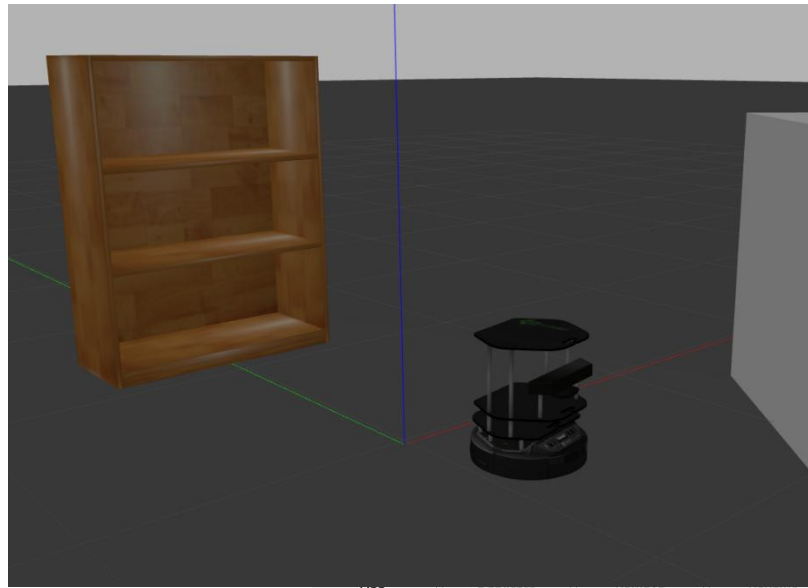
# RGBD information



# TurtleBot in simulation



# Gazebo and RViz



# Literature

---

- Dr. John (Jizhong) Xiao, City College of New York, Robot Sensing and Sensors
- Tod E. Kurt, Hacking Roomba: ExtremeTech, Wiley, 2006
- <http://www.ifixit.com/Teardown/Microsoft-Kinect-Teardown/4066/3>
- Futurepicture, <http://www.futurepicture.org/?p=116>
- United States Patent, Garcia et. al, Patent No. 7,433,024 B2
- Peter Corke, Robotics, Vision and Control, 2017
- other