Human-Robot Interaction

Module 2: How a robot works

Lecture 1: The components, structure, and operation of a robot: robot hardware, sensors, actuators, software, limitations of robotics for HRI

David Vernon
Carnegie Mellon University Africa

www.vernon.eu

The Making of a Robot

- The robot morphology and the robot hardware (sensors and actuators) is selected to match the robot's environment and tasks

- Software provides the functionality: what the robot does with its body

"A robot, in essence, is a computer with a body."
(Bartneck et al. 2020: 19)

Compare this with the following:
"Saying that a robot is embodied does not mean that it is simply a computer on legs or wheels",
(Bartneck et al. 2020: 7)

Body Types

Entertainment

Consumer

Aibo

Aibo is a friendly robotic dog whose personality and behavior evolves over time. It can recognize its owner's face, detect smiles and words of praise, and learn new tricks. And of course, it loves to be petted.

CREATOR
Sony

COUNTRY
Japan 🇯🇵

YEAR
2018

TYPE
Consumer, Entertainment

Source: https://robots.ieee.org/robots/aibo/

Types of Robot

Humanoids

Consumer

Entertainment

Pepper

Pepper is a friendly humanoid designed to be a companion in the home and help customers at retail stores. It talks, gesticulates, and seems determined to make everyone smile.

CREATOR

SoftBank Robotics

(originally created by Aldebaran Robotics, acquired by SoftBank in 2015)

COUNTRY

Japan

YEAR

2014

TYPE

Humanoids, Consumer, Entertainment

Source: https://robots.ieee.org/robots/pepper/

Types of Robot

Consumer

Roomba

Roomba is an autonomous vacuum and one of the most popular consumer robots in existence. It navigates around clutter and under furniture cleaning your floors, and returns to its charging dock when finished.

CREATOR
iRobot

COUNTRY
United States 🇺🇸

YEAR
2002

TYPE
Consumer

Source: https://robots.ieee.org/robots/roomba/

Types of Robot

Education

Roomba

Roomba is an autonomous vacuum and one of the most popular consumer robots in existence. It navigates around clutter and under furniture cleaning your floors, and returns to its charging dock when finished.

CREATOR
iRobot

COUNTRY
United States 🇺🇸

YEAR
2002

TYPE
Consumer

Source: https://robots.ieee.org/robots/roomba/

Types of Robot

Consumer

Telepresence

Beam

Beam is a telepresence robotic system that can "teleport" you to a remote location, allowing you to move around and interact with people. It is easy to drive and has a large display to improve face-to-face, or screen-to-face, communication.

CREATOR
Suitable Technologies

COUNTRY
United States

YEAR
2011

TYPE
Telepresence, Consumer

Source: https://robots.ieee.org/robots/beam/

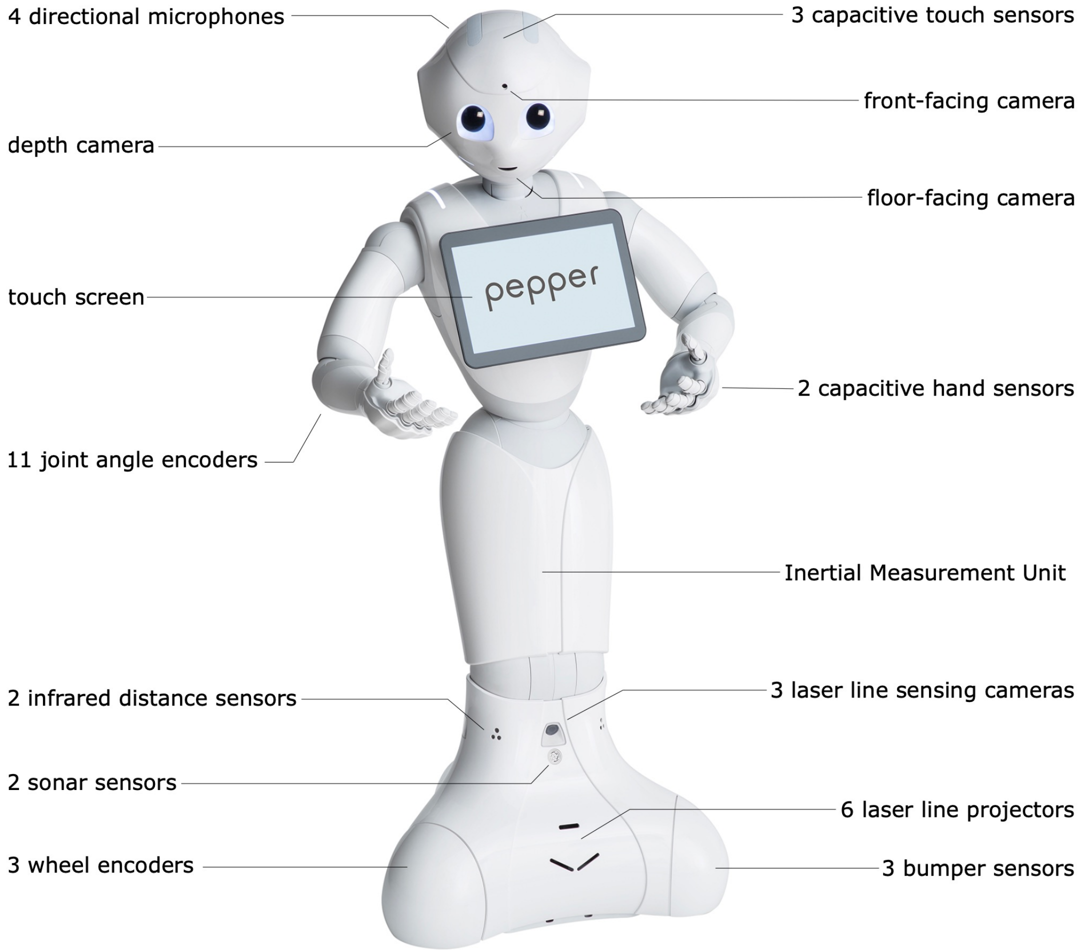
The Making of a Robot

"Every robot is limited in what it can do; its appearance and capabilities constrain the interactions it can engage in."

(Bartneck et al. 2020)

Robot Components

- Robot hardware
- Sensors
- Actuators
- Software



C. Bartneck, T. Belpaeme, F. Eyssel, T. Kanda, M. Keijsers, S. Šabanović, Human-Robot Interaction – An Introduction, Cambridge University Press, 2020

Sensors

Different modalities

- Visual
- Auditory
- Tactile (touch)
- Proximity (distance)
- ...

Vision

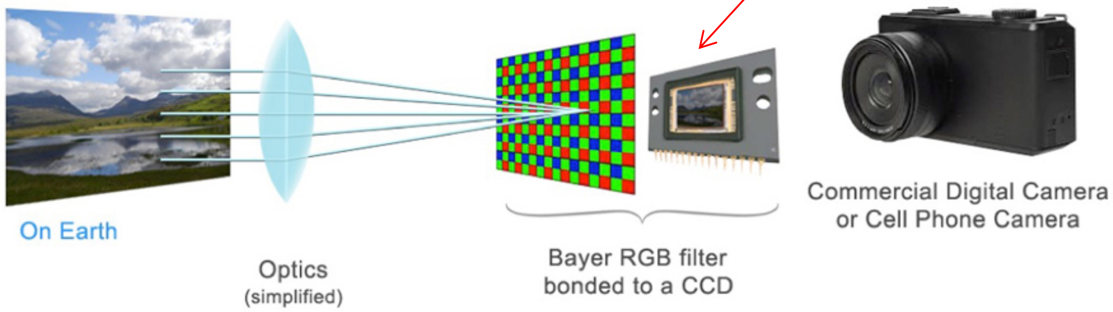
RGB video cameras

R Red

G Green

B Blue

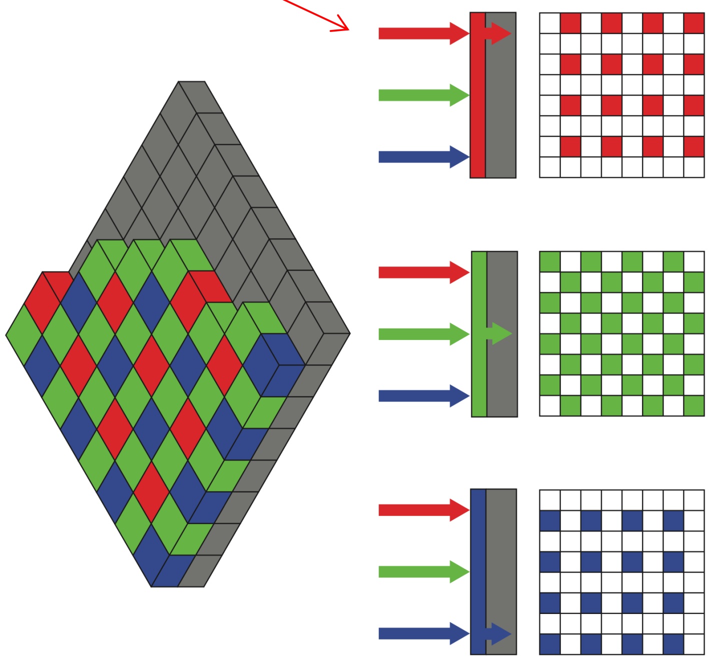
The sensor uses either CCD (charge-coupled device) or
CMOS (complementary metal-oxide-semiconductor) technology
which converts light into electrical energy (charge)



https://www.nasa.gov/mission_pages/msl/multimedia/pia16799.html

Sensors

Since the sensor is sensitive to light of all wavelengths
a colored filter is placed in front of each one in single-sensor cameras
to filter out all lighted except the light that matches the color



C. Bartneck, T. Belpaeme, F. Eyssel, T. Kanda, M. Keijsers, S. Šabanović, Human-Robot Interaction – An Introduction, Cambridge University Press, 2020

Sensors

RGB video cameras

- In some HRI settings, cameras are discouraged because people can feel uncomfortable about possible invasion of privacy

- Other sensors have to be used to provide the information required to interact effectively

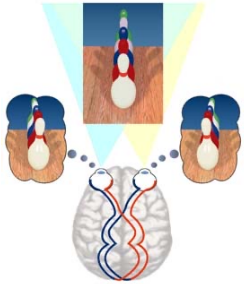
- Most cameras have a more restricted field of view than humans

  - People can see ~180 degrees
  - Many cameras can only see 90 degrees (it depends on the lens)
  - Solution: use more than one camera (see Pepper) or augment with other sensors

Sensors

Depth Sensors

- Stereo (binocular vision; two eyes / cameras)



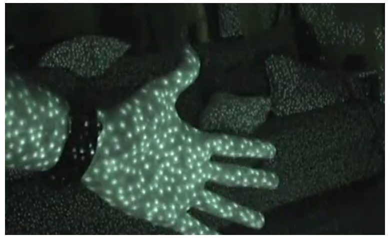
Credit: Markus Vincze, Technische Universität Wien

Sensors

Depth Sensors

- Stereo (binocular vision; two eyes / cameras)
- Structured light (Kinect v1)

- Time of flight ToF (Kinect v2)



Kinect v1: a known infrared pattern is projected into the scene and depth is computed from the distortion of the pattern by the scene

Kinect v2 contains a Time-of-Flight (ToF) camera and determines the depth by measuring the time for emitted light to be reflected back to the camera from the object, i.e. it constantly emits infrared light with modulated waves and detects the shifted phase of the returning light

(Wassenmüller and Stricker 2016)

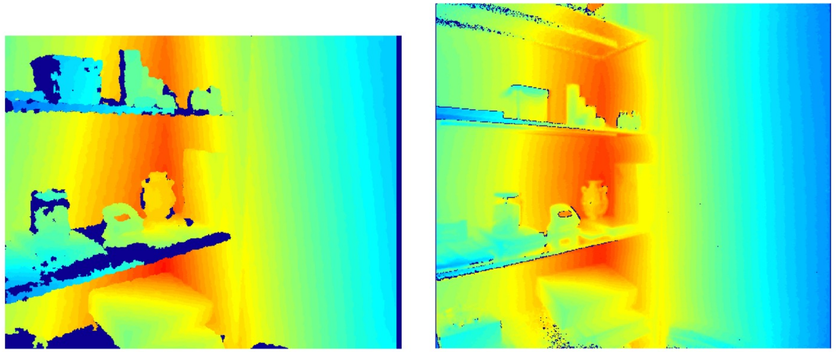
Sensors

Depth Sensors

- Stereo (binocular vision; two eyes / cameras)
- Structured light (Kinect v1)

- Time of flight ToF (Kinect v2)

Comparison of Kinect v1 and v2 Depth Images



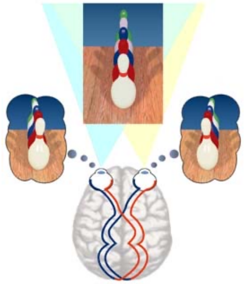
(a) Kinect v1 (b) Kinect v2

(Wassenmüller and Stricker 2016)

Sensors

Depth Sensors

- Stereo (binocular vision; two eyes / cameras)

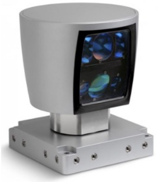


Credit: Markus Vincze, Technische Universität Wien

- Structured light
  (Kinect v1)

- Time of flight ToF
  (Kinect v2)

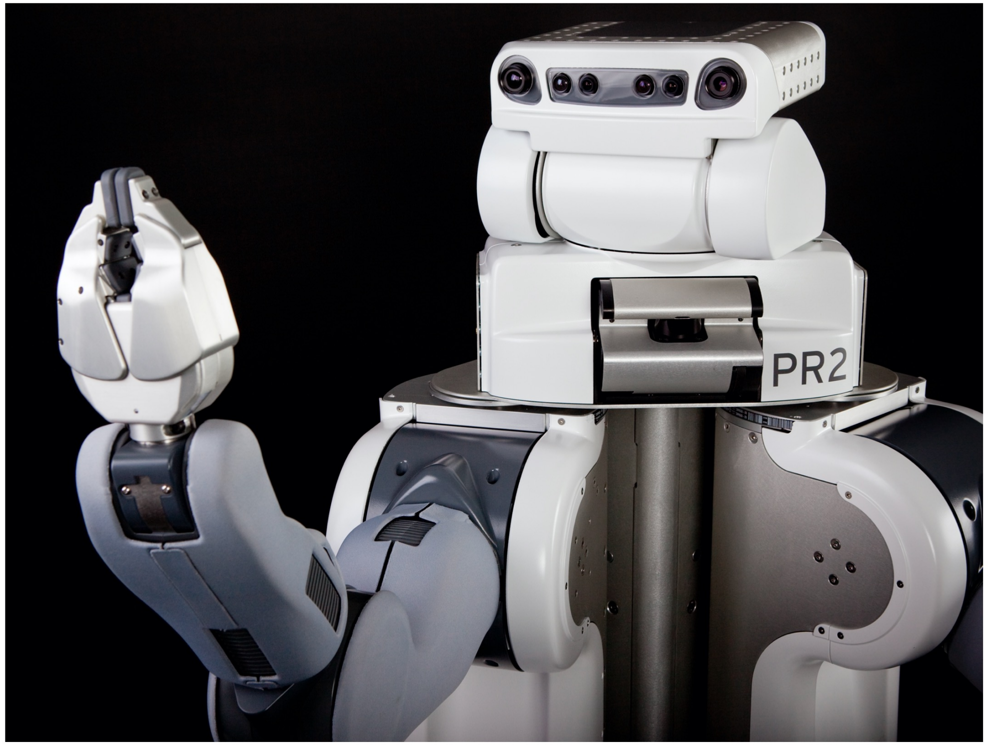
- LiDAR (laser Light Detection And Ranging)



Sensors

Depth Sensors

- Laser time of flight sensor (LIDAR) on PR2 robot
- Scans in a plane
- Plane is tilted in the vertical direction to get a 2D depth image



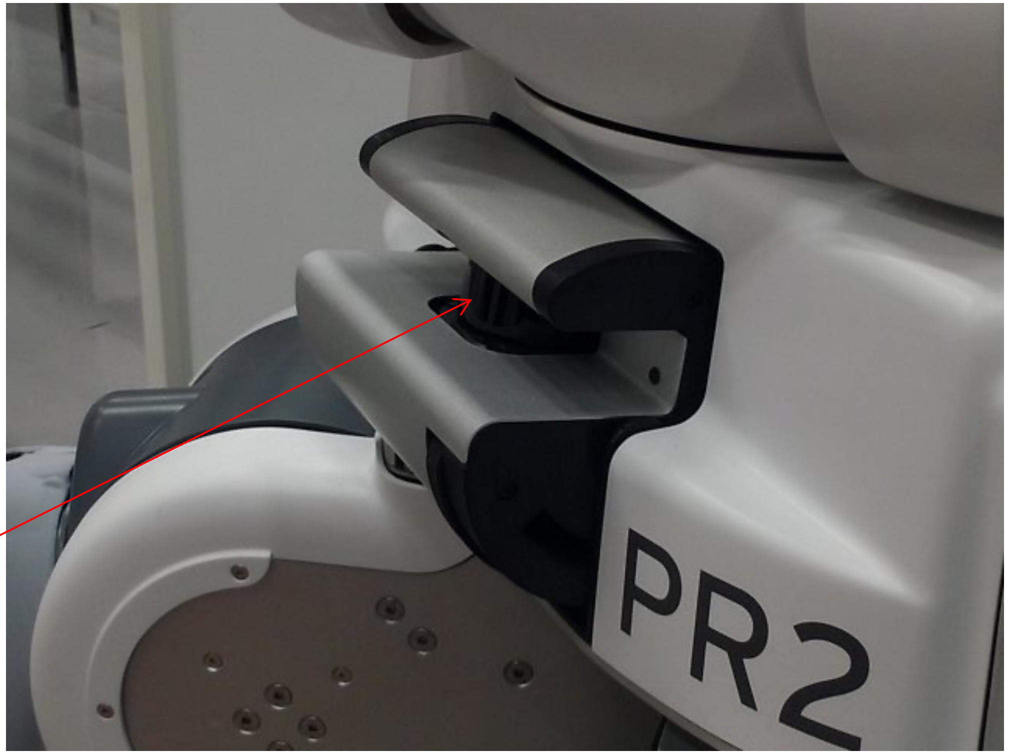
C. Bartneck, T. Belpaeme, F. Eyssel, T. Kanda, M. Keijsers, S. Šabanović, Human-Robot Interaction – An Introduction, Cambridge University Press, 2020

Sensors

Depth Sensors

- Laser time of flight sensor (LiDAR) on PR2 robot
- Scans in a plane
- Plane is tilted in the vertical direction to get a 2D depth image

Hokuyo Lidar

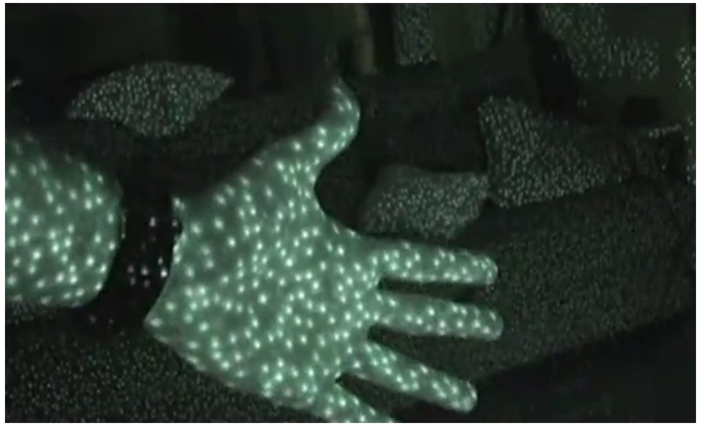


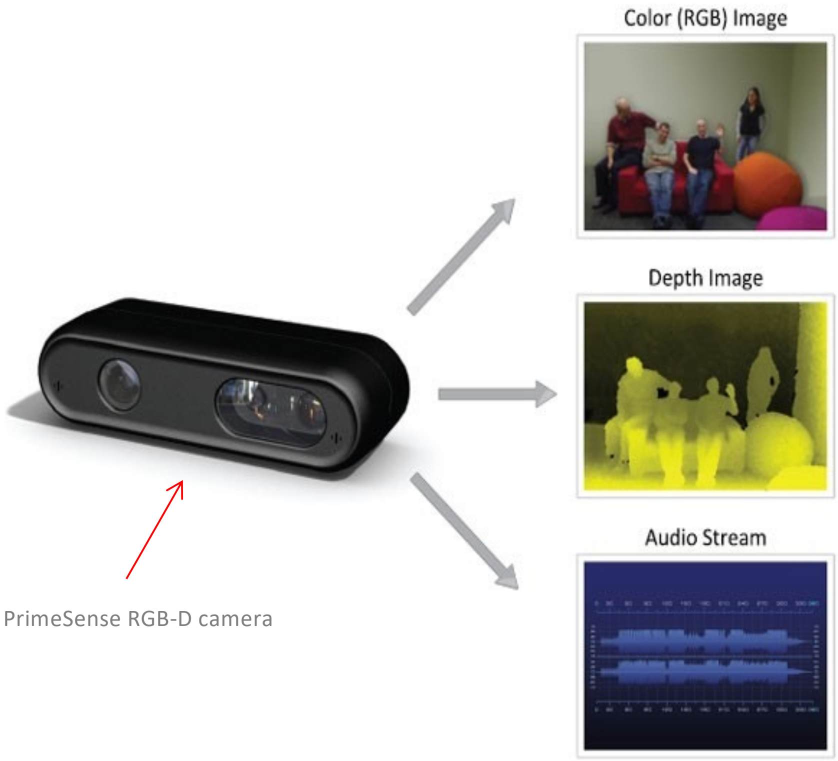
(Wassenmüller and Stricker 2016)

Sensors

Depth Sensors are often combined with RGB cameras: RGB-D

- Distance: 0.8 – 3.5 m
- Spatial x/y resolution 3mm @ 2m
- Depth z resolution: 10mm @ 2m
- Sunlight reduces visibility of the infrared pattern



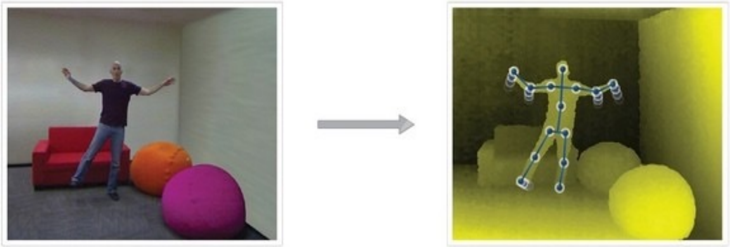


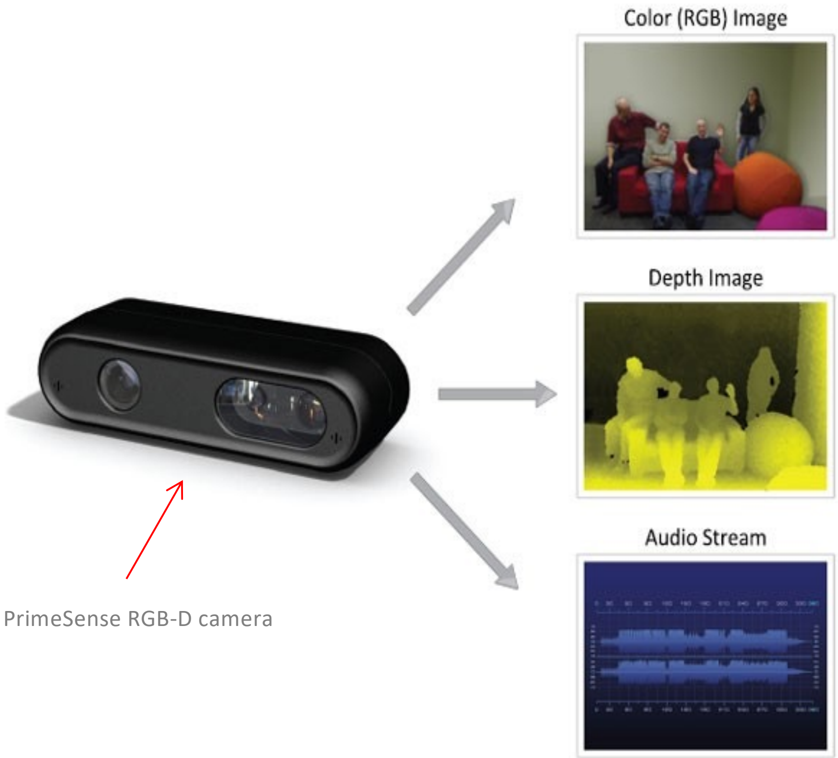
Credit: Markus Vincze, Technische Universität Wien

Sensors

Depth Sensors are often combined with RGB cameras: RGB-D

- Distance: 0.8 – 3.5 m
- Spatial x/y resolution 3mm @ 2m
- Depth z resolution: 10mm @ 2m
- Sunlight reduces visibility of the infrared pattern





Credit: Markus Vincze, Technische Universität Wien

Sensors

Depth Sensors are often combined with RGB cameras: RGB-D

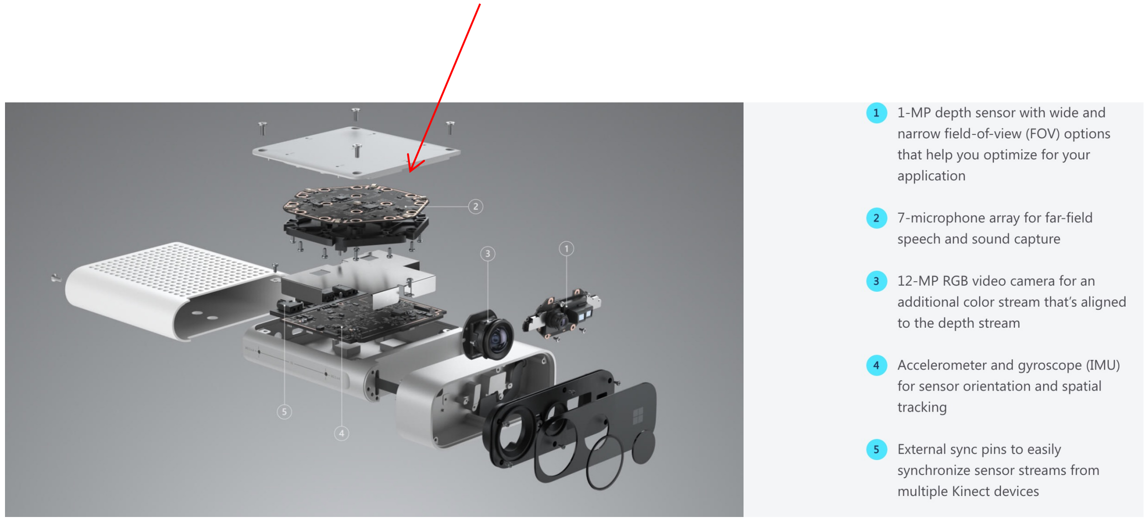
The Microsoft Azure Kinect DK sensor

https://azure.microsoft.com/en-us/topic/mixed-reality/#demystifying

Example: Sensor by PrimeSense

Audio

- Microphones are used for auditory sensing
- Different sensitivity profiles: omnidirectional, directional
- Combining multiple microphones into an array allows the use of "beam-forming" techniques
  - Separate sound signals coming from a specific direction from ambient sound
  - Sound localization: direction of arrival of sound with respect to the microphone array



Sensors

Tactile Sensors

- Physical buttons or switches: contact

- Capacitive sensors: pressure
  - Useful when a robot needs to know how hard it is touching something
  - Also useful when a robot needs to know if someone is touching it

Sensors

Tactile Sensors

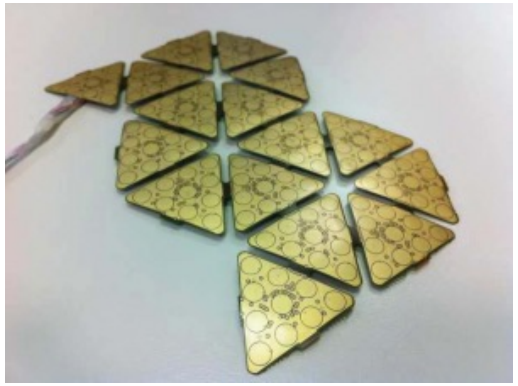
- Physical buttons or switches: contact

Bumper switches

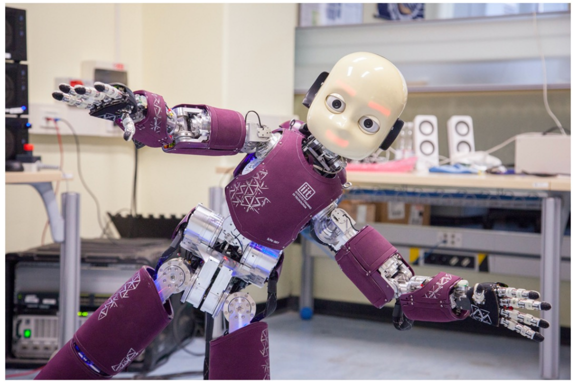
- Capacitive sensors: pressure
  - Useful when a robot needs to know how hard it is touching something
  - Also useful when a robot needs to know if someone is touching it

18 patches, each comprising 10 taxels

1 in each hand
2 in each forearm
4 in each upper arm
4 in the torso



http://wiki.icub.org/wiki/Tactile_sensors_(aka_Skin)

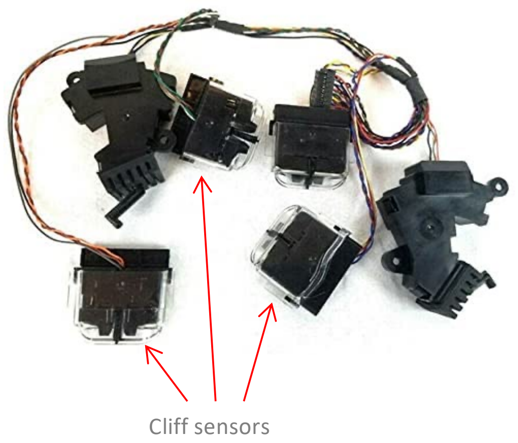


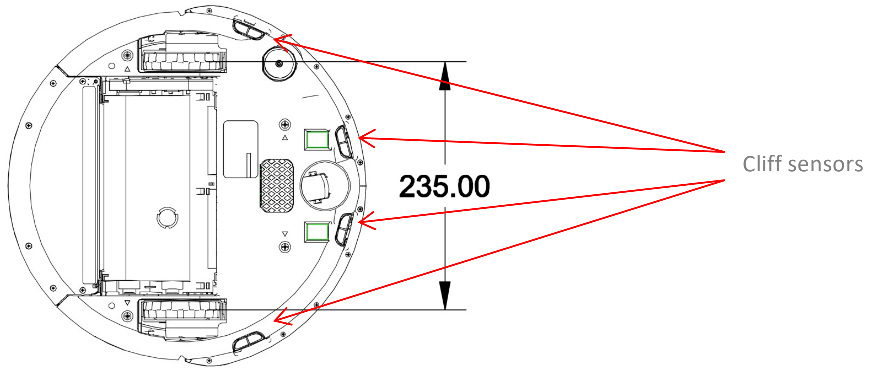
Bartneck et al. 2020)

Sensors

Light Sensors

- Combined with a light source (e.g. LED)
- Can be used to detect objects
- Can be used to detect absence of objects, e.g. iRobot Create 2 cliff sensors



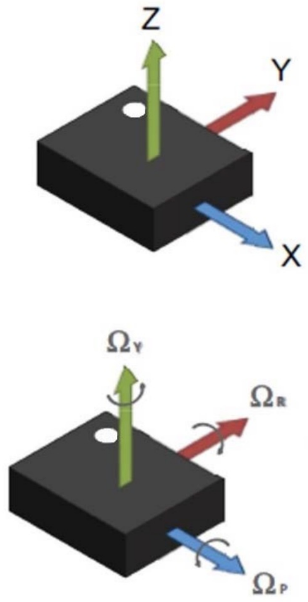


Sensors

Inertial Measurement Unit IMU

- Combines three accelerometers and three gyroscopes
- In three orthogonal (x, y, z) directions
- To sense change in position and orientation

Accelerometers sense change in position
Gyroscopes sense change in orientation



Source:
https://www.st.com/resource/en/datasheet/asm330lhh.pdf

Sensors

Options for detecting change in relative position:

- Accelerometers sense acceleration … we want change in position
- Gyroscopes sense rate of change of orientation … we want change in orientation
- We get what we want by integrating the sensed data with respect to time

Sensors

Joint angle & angular velocity encoders

Joint torque sensor

Inertial Measurement Unit (IMU)
accelerometer and gyroscope sensors

RGB video cameras

Depth cameras

RGB-D cameras

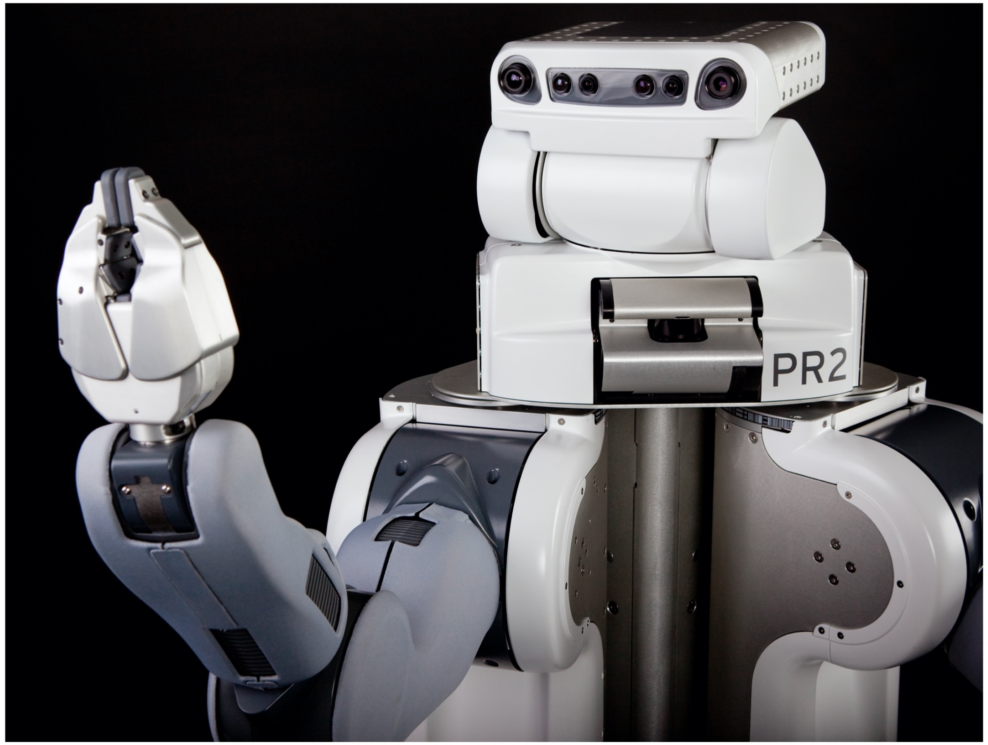
Microphone audio sensors

Capacitive touch sensors

Laser distance sensors

Ultrasonic distance sensors

Bumper touch sensors



C. Bartneck, T. Belpaeme, F. Eyssel, T. Kanda, M. Keijsers, S. Šabanović, Human-Robot Interaction – An Introduction, Cambridge University Press, 2020

Robot Components

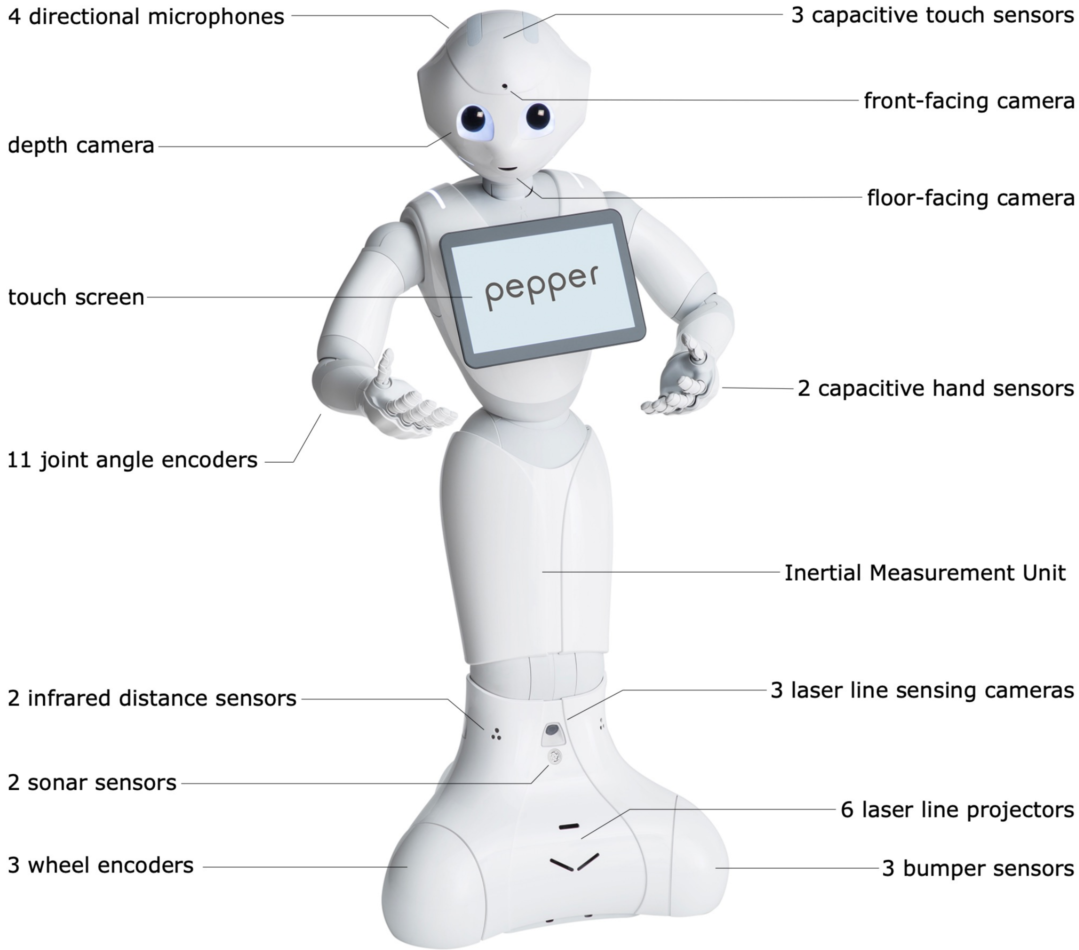
- Robot hardware
- Sensors
- Actuators
- Software

We usually distinguish between actuators and effectors

Effectors are the mechanisms that the robot uses to interact physically with its environment: wheels, legs, arms, fingers, ...

Actuators are the mechanisms that physically move the effectors: motors, pneumatic actuators, hydraulic actuators

Bartneck et al. (2020) don't make this distinction



C. Bartneck, T. Belpaeme, F. Eyssel, T. Kanda, M. Keijsers, S. Šabanović, Human-Robot Interaction – An Introduction, Cambridge University Press, 2020

Definition

- An actuator converts electrical signals into physical movements
- A system with one actuator realizes motion either on
  - one straight line (linear actuators)
  - one rotational axis (rotary actuators)
- This means the system has one degree of freedom
- By combining multiple actuators, we can develop a robot that has motion with multiple degrees of freedom (e.g., for navigating on a 2D surface or gesturing in a 3D space)

Linear vs. Rotary Actuators

- Linear Actuators

  The shaft of the linear actuators moves along its axis

- Rotary actuators

  The shaft of the rotary actuator rotates about its axis

Types of Actuator

- Direct current (DC) motors
- Pneumatic actuators
- Hydraulic actuators
- Speakers

C. Bartneck, T. Belpaeme, F. Eyssel, T. Kanda, M. Keijsers, S. Šabanović, Human-Robot Interaction – An Introduction, Cambridge University Press, 2020

Direct Current (DC) Motors

https://robocademy.com/2020/04/13/how-to-choose-an-actuator-for-your-robot/

Direct Current (DC) Servo Motors

- Direct current (DC) servo motors
- Pneumatic actuators
- Hydraulic actuators
- Materials that are sensitive to light, heat, or chemicals can also be used as actuators

C. Bartneck, T. Belpaeme, F. Eyssel, T. Kanda, M. Keijsers, S. Šabanović, Human-Robot Interaction – An Introduction, Cambridge University Press, 2020

Direct Current (DC) Servo Motors

- DC motors rotate continuously in one direction

- Often, we need a motor that can move an effector to a particular position

- Motors that turn the shaft to a specific position are called servo motors (or servos, for short)

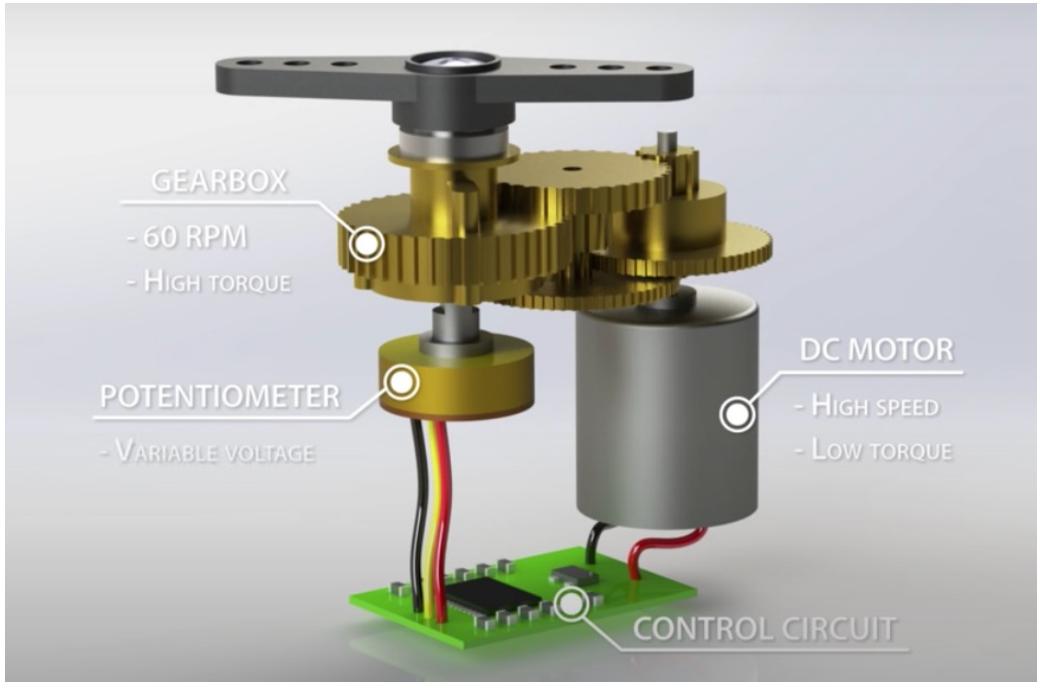
Used in the shoulder joint of the Lynxmotion AL5D robot arm

https://www.robotshop.com/en/hs-805bb-giant-scale-servo-motor.html

Direct Current (DC) Servo Motors

Direct current (DC) servo motor:

- DC motor
- Gearbox for gear reduction
- Position sensor for the output shaft
- Control circuit
  - Direction of rotation
  - Angle of rotation (+/- 180 degrees)



https://robocademy.com/2020/04/13/how-to-choose-an-actuator-for-your-robot/

Direct Current (DC) Servo Motors

Position sensor

- Potentiometer
- Encoder

which outputs the absolute or relative position of the motor's output shaft

Direct Current (DC) Servo Motors

Control circuit

- Typically uses a form of pulse-width modulation (PWM)
  - PWM uses on/off pulses to switch the motor on for a few milliseconds and then back off again
  - This is done several time per second (e.g. 50 hz or 100 hz)
  - The duration of the on phase against the off phase is known as the duty cycle
  - The duty cycle determines the speed at which the motor rotates
- The PWM signal controls the speed of the motor
- The controller sets the position of the motor through feedback control
  - The controller continuously reads the position of the motor (using the potentiometer or encoder)
  - Adjusts the motor's PWM and direction to reach or maintain a desired position

Direct Current (DC) Servo Motors

- For motors used in a robot's arms, legs, and head
  - the controller typically performs position control to rotate the motor toward a given joint angle
  - Also performs velocity control and torque (force x distance) control
- For motors used in wheels on a mobile base
  - the controller typically performs velocity control to rotate the motor at the required joint velocity

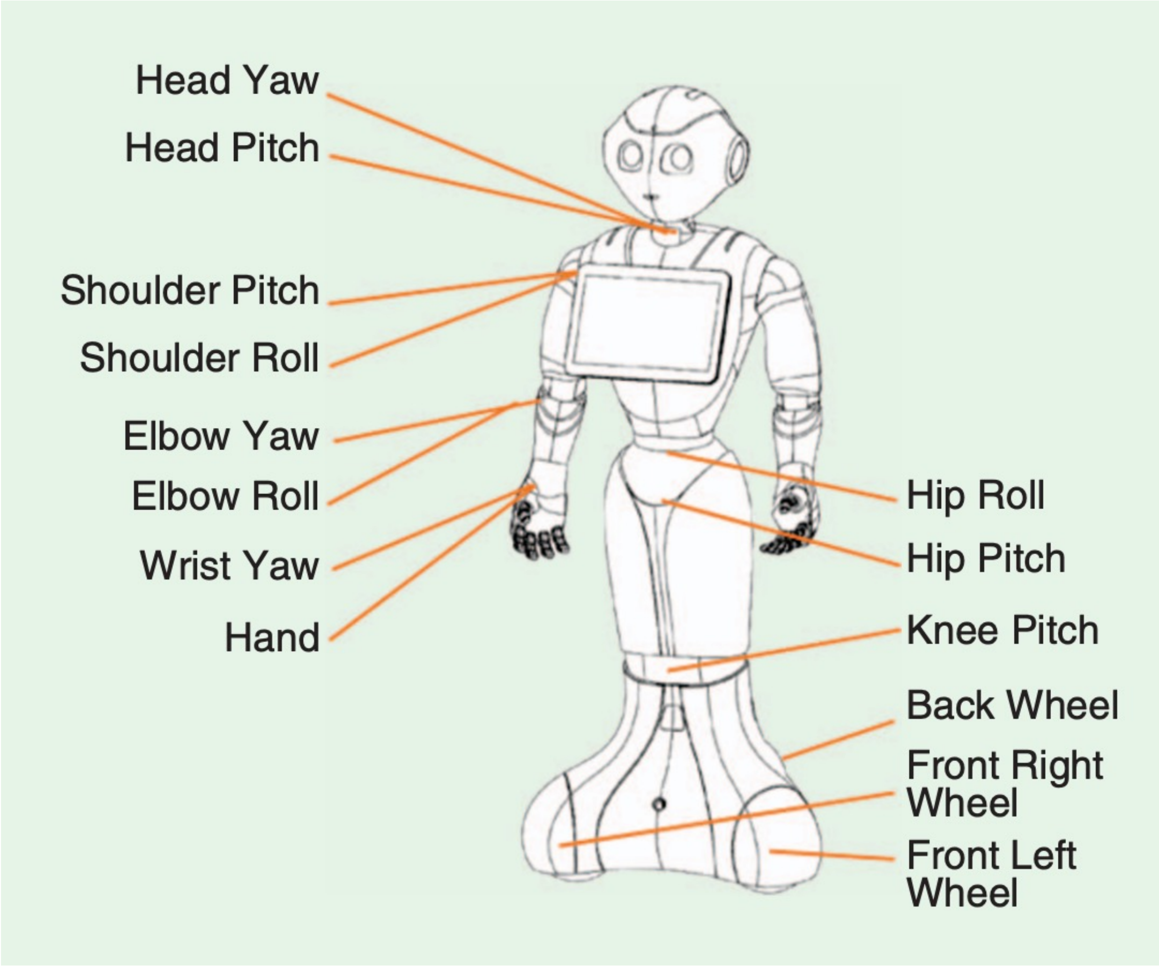
Robot Configurations

https://store.irobot.com/default/create-programmable-programmable-robot-irobot-create-2/RC65099.html

Two motors driving two wheels
and two degrees of freedom

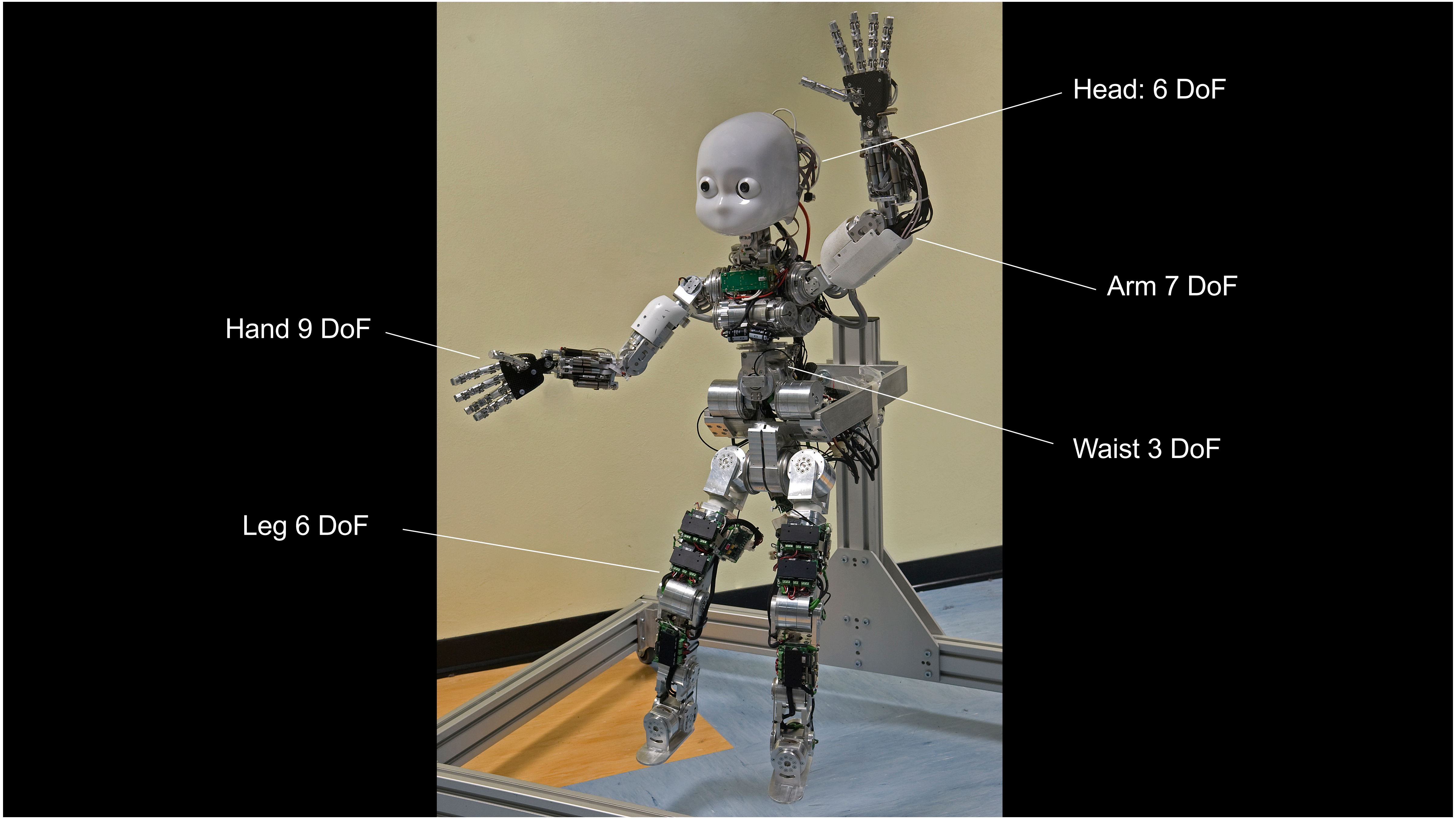
https://homesupport.irobot.com/s/article/20711

Robot Configurations



IEEE Robotics and Automation Magazine, September 2018, pp. 40-48

https://robots.ieee.org/robots/pepper/

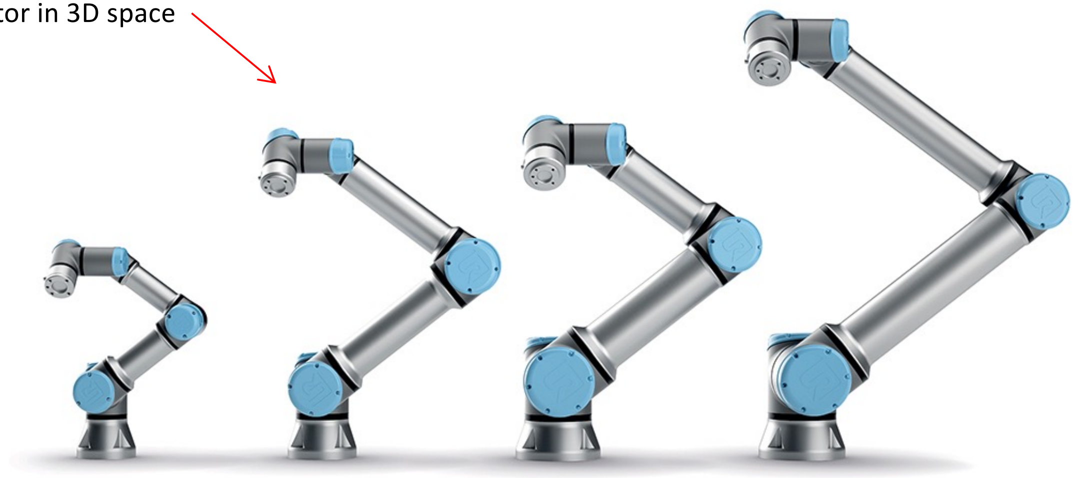

Head: 6 DoF
Arm 7 DoF
Hand 9 DoF
Waist 3 DoF
Leg 6 DoF

Robot Configurations

Six degree of freedom industrial manipulator:
Three to position the wrist in 3D space
Three to orient the wrist/end effector in 3D space

KUKA LBR iiwa

https://robots.ieee.org/robots/lbriiwa



Universal Arms

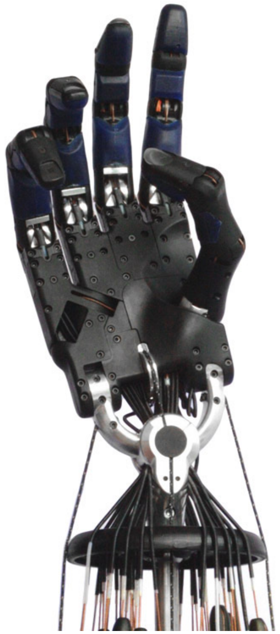
https://robots.ieee.org/robots/lbriiwa

Robot Configurations

End-effector to grasp objects

1-DOF gripper

20-DOF dextrous hand



https://robots.ieee.org/robots/shadow/

Robot Configurations

Android robots can have many DOFs (e.g. 50 DOFs) and are able to control their facial expressions and other bodily movements

https://robots.ieee.org/robots/geminoiddk/?gallery=photo4


Video
https://robots.ieee.org/robots/geminoiddk/?gallery=video1
http://www.robotplatform.com/knowledge/actuators/types_of_actuators.html

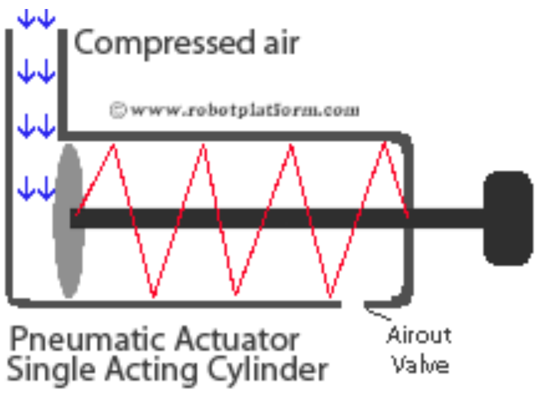
Direct Current (DC) Servo Motors

When designing a robot, it is important to make sure the motor specifications match the requirements

- Wave its arms vs. lift a heavy payload
- How big the robot can be and still fit in well in its environment
- How quickly it needs to respond to stimuli
- Whether it has to run on a portable power bank or will always be plugged in

Pneumatic Actuator

- Compressed air creates a force that moves
  - Diaphragm
  - Piston
- Large & powerful
- Potentially dangerous
- Need to prevent leaks

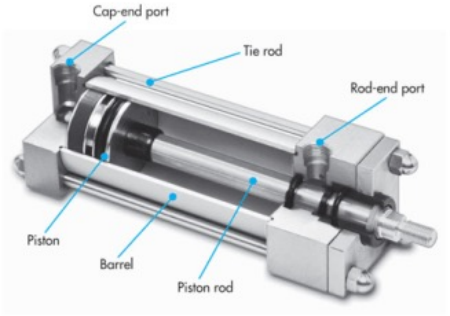


http://www.robotplatform.com/knowledge/actuators/types_of_actuators.html

Pneumatic Actuator

- Compressed air creates a force that moves
  - Diaphragm
  - Piston
- Large & powerful
- Potentially dangerous
- Need to prevent leaks

Pneumatic actuator



Section of pneumatic actuator

https://robocademy.com/2020/04/13/how-to-choose-an-actuator-for-your-robot/

Pneumatic Actuator

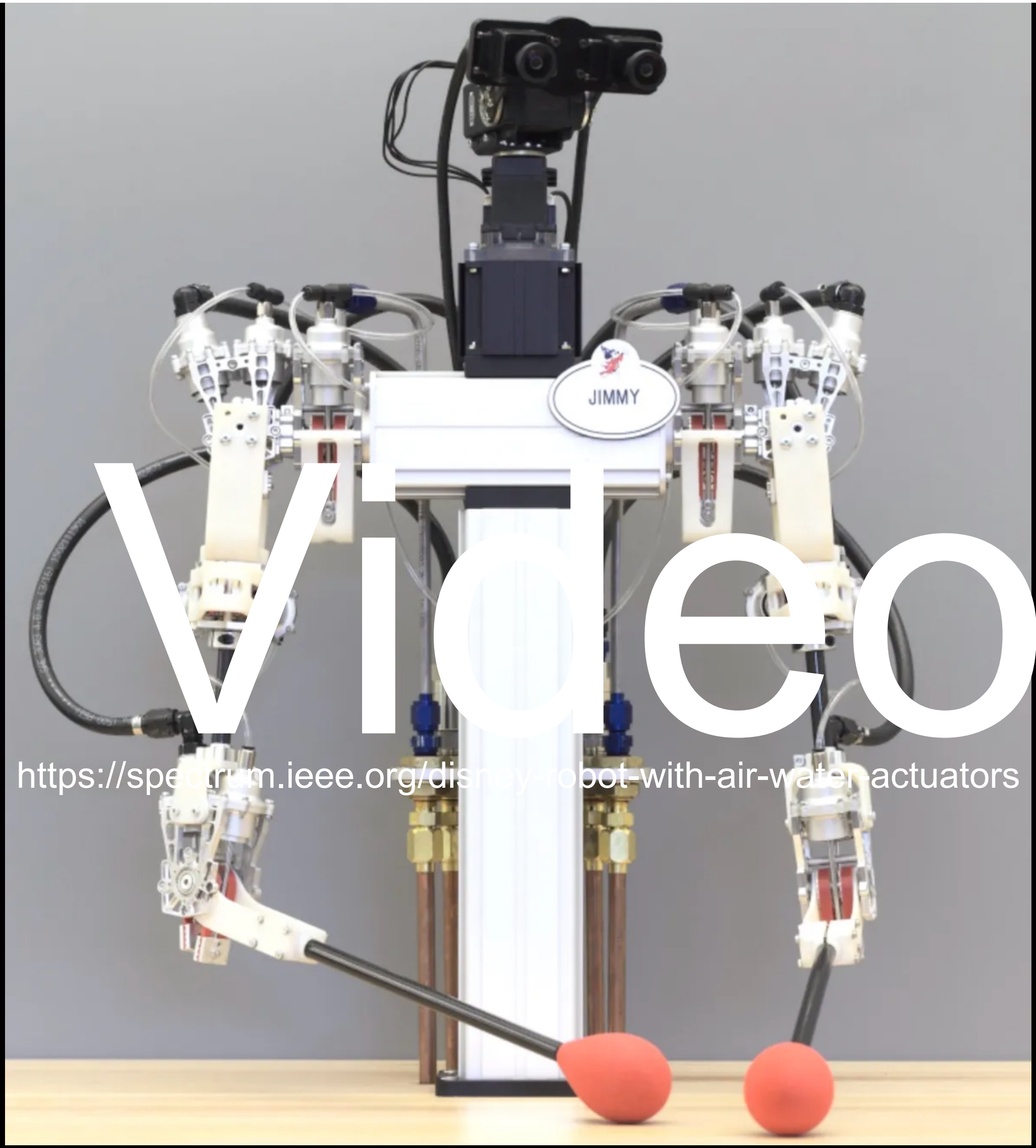
Often preferred for humanoid robots and android robots

- Need to gesticulate at humanlike velocity and acceleration
- The compressors can be quite loud
- This might disrupt the interaction experience

https://robots.ieee.org/robots/robothespian/?gallery=photo2

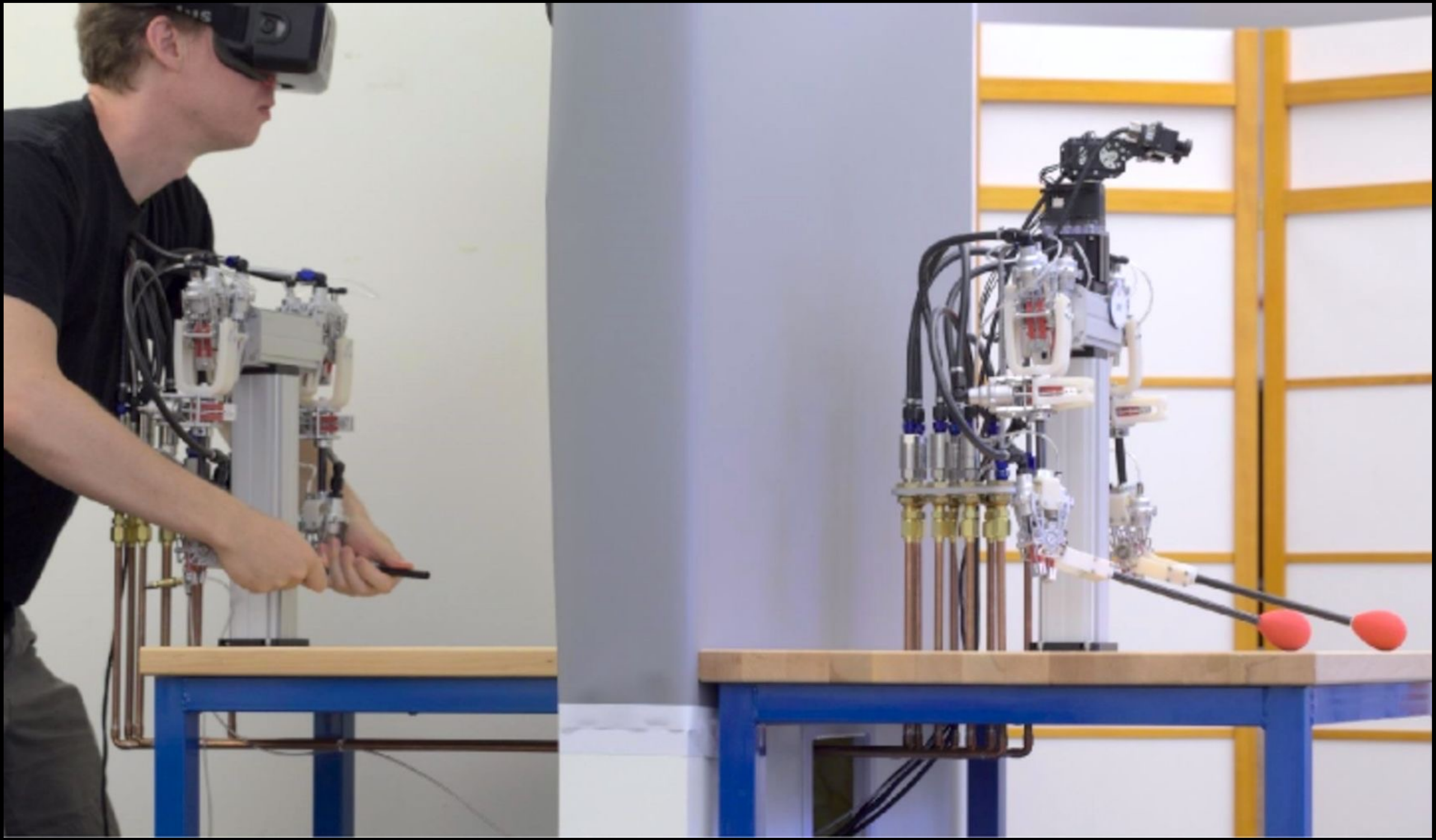
Video

https://robots.ieee.org/robots/robothespian/?gallery=video1



Video

https://spectrum.ieee.org/disney-robot-with-air-water-actuators



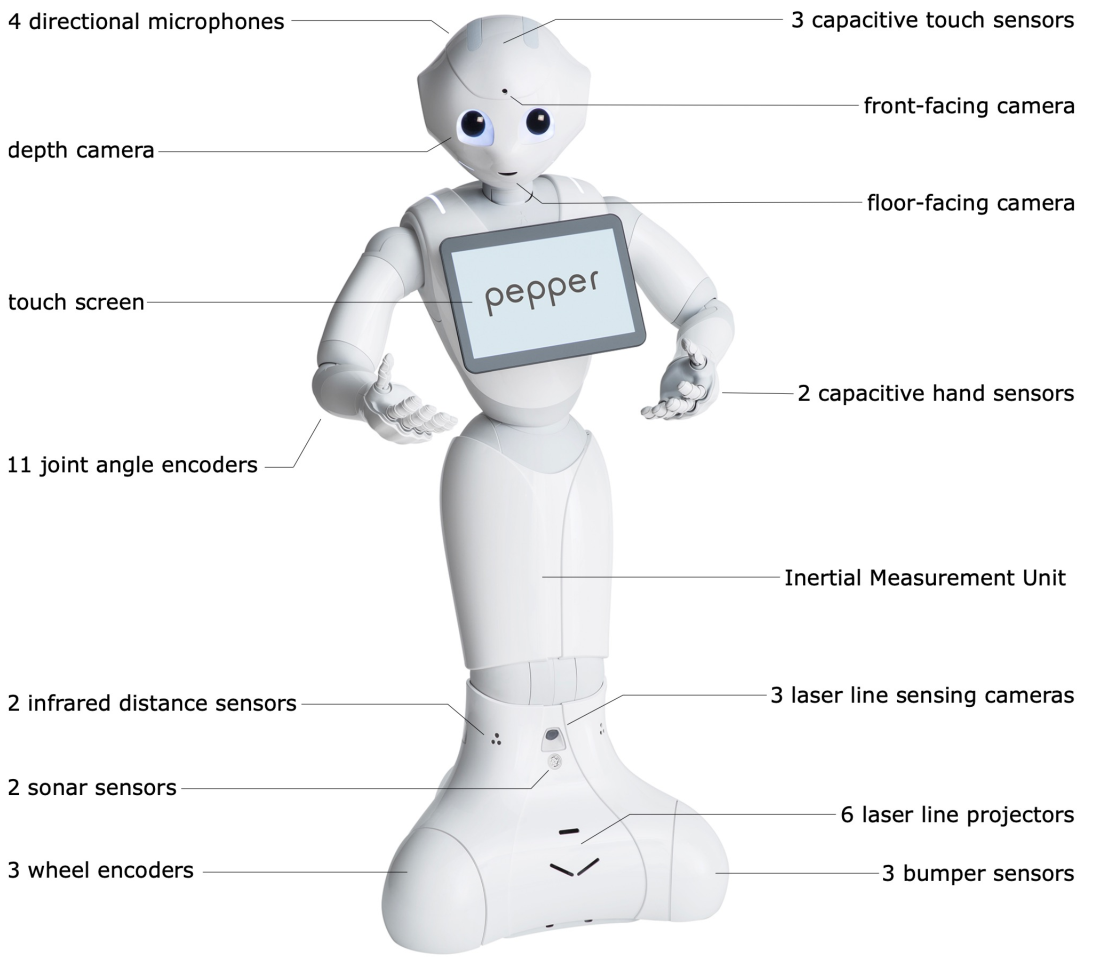
https://spectrum.ieee.org/disney-robot-with-air-water-actuators

Speakers

- Standard loudspeakers are used to generate sounds and speech
- Indispensible for HRI
- Speaker placement is an issue
  - Relative height from which the voices of a user and an agent interacting are projecting
  - Impacts the perception of dominance in the interaction

Robot Components

- Robot hardware
- Sensors
- Actuators
- Software



C. Bartneck, T. Belpaeme, F. Eyssel, T. Kanda, M. Keijsers, S. Šabanović, Human-Robot Interaction – An Introduction, Cambridge University Press, 2020

Software

All currently available robots are controlled by software

- One or more computers
- On-board or remote, possibly cloud-based
- Cloud-based services offer far more power
- But at the cost of requiring robust internet connectivity, not always guaranteed
- Time-critical and safety-critical processing are usually done on-board

Software

- A robot interfaces with a messy real world
- And needs to make sense of it in real time

"A robot is much more than computer with a body."
(Bartneck et al. 2020: 31)

Compare this with the following:
"A robot, in essence, is a computer with a body."
(Bartneck et al. 2020: 19)

Software

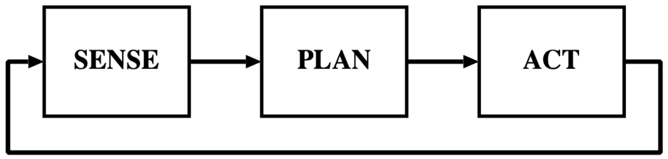
- The software needs to be organized
  - Modularized
  - Using a software architecture
- There are different architecture models
  - Each implement a different control strategy

Software Architecture Models

- Sense-plan-act / Deliberative / Hierarchical
- Reactive
- Behaviour-based

Software Architecture Models

- Sense-plan-act / Deliberative / Hierarchical
- Reactive
- Behaviour-based



Input sensory data

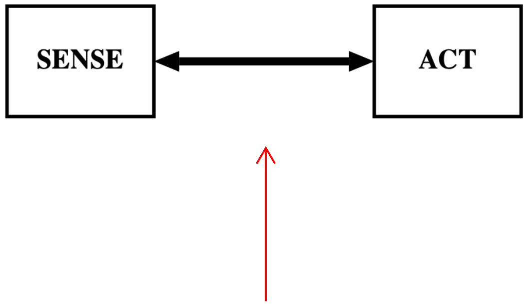
Processed into abstract representations

Analyzed to plan the next action

Output the action motor commands

Software Architecture Models

- Sense-plan-act / Deliberative / Hierarchical
- Reactive
- Behaviour-based



Act first; think later

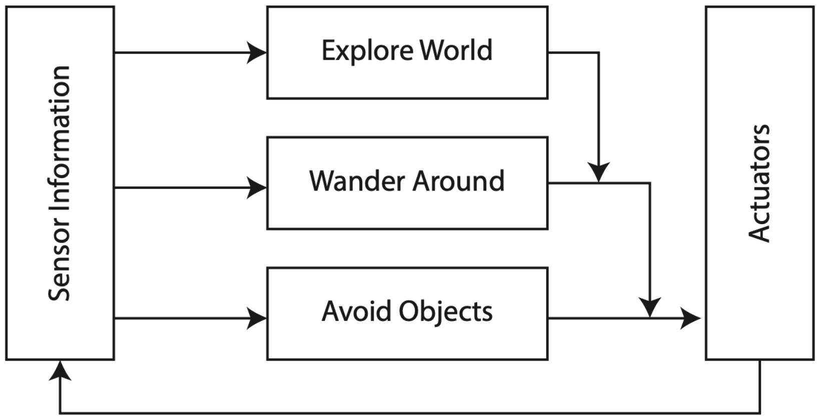
Multiple instances of Sense-Act couplings called sensorimotor contingencies or behaviors

Each behavior operates in parallel

Advantage: immediately respond to an external event

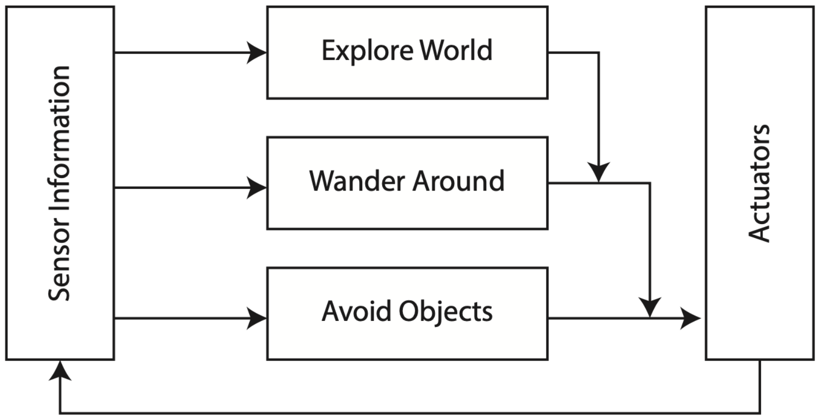
Software Architecture Models

- Sense-plan-act / Deliberative / Hierarchical
- Reactive
- Behaviour-based
  - Invoke mechanisms to mediate between which behaviors are active and which are not
  - For example, the subsumption architecture which organizes behaviors into hierarchies



Software Architecture Models

- Sense-plan-act / Deliberative / Hierarchical
- Reactive
- Behaviour-based
  - While not having an explicit representation of the world, it can still behave in an "apparently" intelligent way
  - Cleaning robot: two behaviors in parallel
    1. Avoid walls
    2. Steer slightly to the right
    - The resulting, emergent, behavior is "wall-following"
    - The iRobot Roomba was developed with this in mind



Software Architecture Models

- Sense-plan-act / Deliberative / Hierarchical
- Reactive
- Behaviour-based
- Hybrid of deliberative and reactive
  - HRI typically requires a middle ground between deliberative and reactive
  - A reactive control layer that responds quickly to sub-second social events
  - A deliberative layer, which formulates a coherent response to slower elements in the interaction, e.g. a conversation

Software-implementation Platform

Robot Operating System (ROS)

- Commonly used for robotics and HRI
- Provides a way for individual modules to communicate
- Provides libraries and tools for common robot abilities
  - Localization
  - Navigation
- Large community who share public software repositories

Machine Learning

Let a robot learn a skill rather than programming it explicitly. To do this, we need

- Training data
  - A large number of examples of what has to be learned (~1000 per instance)
  - Typically, manually annotated or labelled
- Feature extraction
  - A feature is a number that indicates the degree to which the data exhibits a particular characteristic (e.g. timbre, frequency, age, height, local contrast, color...)
  - Typically n features are assembled together in an n-dimensional feature vector
- Machine learning algorithm
  - Many options: supervised, unsupervised, reinforcement, for classification, regression, or policy
  - We want the learning algorithm to generalize (correctly handle unseen data) but not overfit (good performance on training data, poor performance on unseen data)

Machine Learning

Deep Learning

- Deep neural networks with a large number of layers

- Training requires significant computational power
  - Made possible by recent availability of graphic processing units (GPUs) & parallel processing

- Feature extraction is done automatically by the network: learning the features that are required

- Very large datasets required
  - e.g., 230 billion data points are used by Google to train it speech recognition network
  - Major problem for HRI because it is difficult to collect large amounts of data where humans and robots interact

- Lack of explainability is also an issue
  - Deep neural networks tend to be black boxes (but this is changing)
  - Impacts negatively on trustworthiness of the network

Computer Vision

- Important for HRI
  - Motion detection
  - Face detection
  - Face recognition (still a challenge, especially side-on views)
  - Gesture recognition
  - Skeleton tracking (for activity recognition), often using RGB-D cameras using, e.g. OpenPose
- Open libraries, e.g. OpenCV, make it easier to implement
- Sometimes implemented in the cloud, streaming the data to servers
- Significant progress through advances in deep learning
  - Recent advances in skeleton tracking using RGB cameras

Limitations of Robotics for HRI

General challenges

- System complexity: integration of many sub-systems is non-trivial
  - Natural language processing
  - Speech recognition
  - Social-signal processing
  - Face detection
  - Emotion classification
  - Sound-source localization
  - Action selection
  - Navigation

Limitations of Robotics for HRI

General challenges

- Significant gap between
  - The noisy, uncertain, analogue world of robotics and
  - The digital domain
- Learning
  - Deep learning can take days and weeks
  - Robots operate in real-time
  - Skill transfer from one task to another is still a major challenge

Limitations of Robotics for HRI

General challenges

- Robots and AI systems struggle with semantics
  - They don't truly understand what happens around them
  - They may exhibit the appearance of intelligent behavior, without being intelligent
  - Many such behaviors are pre-programmed and are not grounded
    - cf. Searle's Chinese Room: computers only process syntactic symbols that do not contain semantics
    - cf. McDermott: AI doesn't need to replicate human mechanisms of intelligence to be considered intelligent
    - Continual shift in what people deem to constitute an artificially intelligent agent

Limitations of Robotics for HRI

General challenges

- Researchers often fake the intelligence of a robot by applying the Wizard-of-Oz method
- "In the field of human–computer interaction, a Wizard of Oz experiment is a research experiment in which subjects interact with a computer system that subjects believe to be autonomous, but which is actually being operated or partially operated by an unseen human being"

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

https://www.researchgate.net/publication/228830650_How_to_design_and_prototype_an_information_appliance_in_24_hours-Integrating_product_interface_design_processes

Limitations of Robotics for HRI

General challenges

- Researchers often fake the intelligence of a robot by applying the Wizard-of-Oz method

- "In the field of human–computer interaction, a Wizard of Oz experiment is a research experiment in which subjects interact with a computer system that subjects believe to be autonomous, but which is actually being operated or partially operated by an unseen human being"

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

- The requirements of HRI often imply unrealistic expectations about what is feasible with current technology

- Take-home message: novice researchers and the general public need to be aware of the current limitations of robotics and AI

Reading

Bartneck, C., Belpaeme, T., Eyssel, F., Kanda, T., Keijsers, M., Sabanovic, S. (2020). Human-Robot Interaction - An Introduction, Cambridge University Press.

Chapter 3 – How a Robot Works, pp. 18-40