Sensory robotics

Lecture 07.

i.) Sensors for localization and navigation
ii.) Collision, touch, pressure, force and temperature sensing
iii.) Sensing the inner state

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SLAM (simultanous localization and mapping)

- DARPA Challenge 2004, 2005
- Odometry (odos~ „route” and metron~ „measure”): calculates the position using inner sensors (rotation of wheels, encoders, gyroscopes, compass, accelerometers, IMUs, etc.). Inaccurate because it accumulates the error of the measurements.
- SLAM: The robot updates (and corrects) its odometry calculated position with measuring its relative position to the environment using distance measurement sensors. The process builds a map and update the robot’s position simultanously.

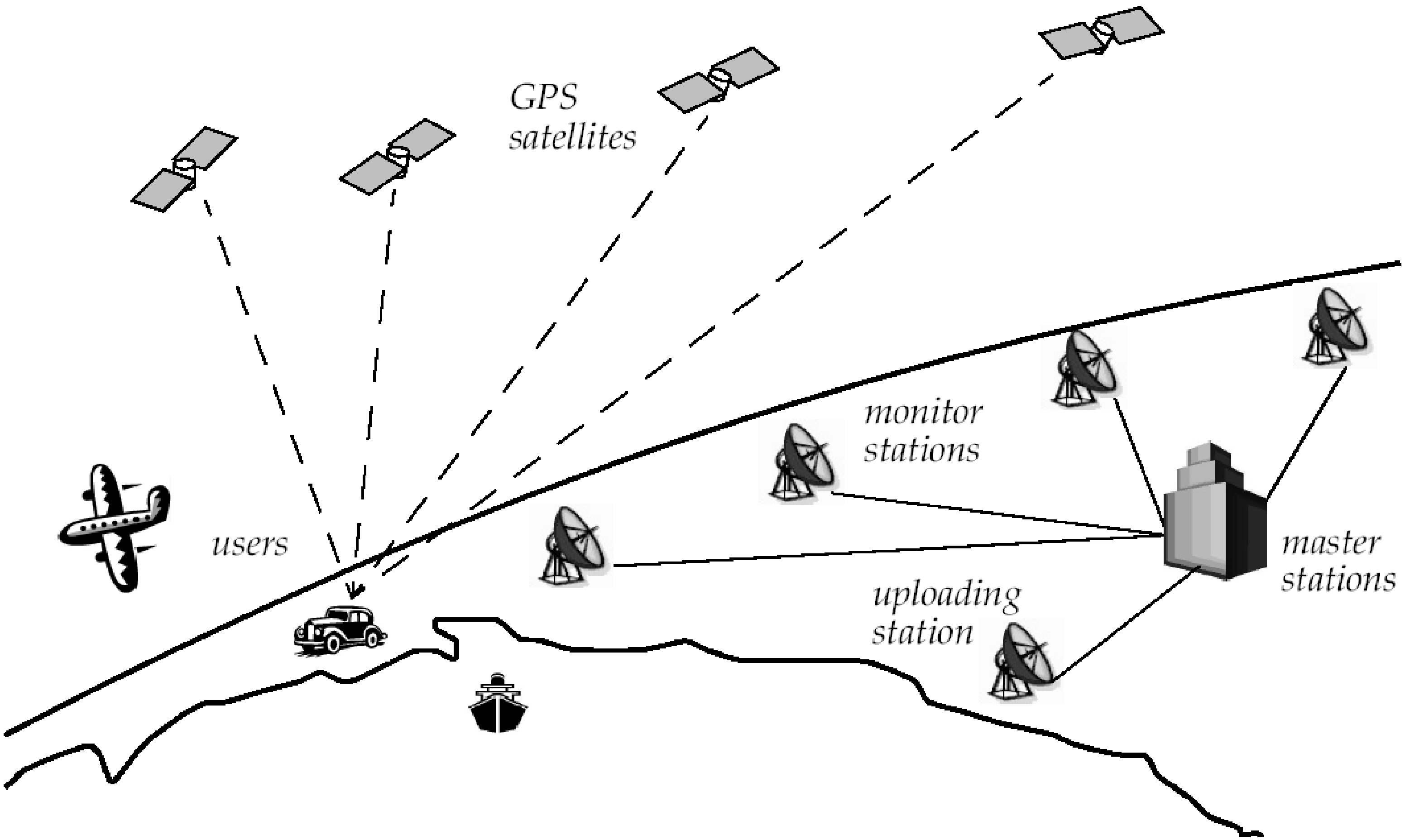
References

- *Roland Siegwart, Illah R. Nourbakhsh, Davide Scaramuzza: Autonomous Mobile Robots*
- *H. R. Everett, A. K. Peters: Sensors for mobile robots: theory and applications, 1995, ISBN: 1-56881-048-2*

Global Positioning System (GPS) (1)

- Facts
  - Became accessible for commercial applications in 1995
  - Initially there were 24 satellites orbiting the earth every 12 hours at a height of 20.190 km.
  - 4 satellites were located in each of 6 orbits with 60 degrees orientation between each other.
- Working Principle
  - Location of any GPS receiver is determined through a time of flight measurement (satellites send orbital location (*ephemeris*) plus time; the receiver computes its location through **trilateration** and **time correction**)
- Technical challenges:
  - **Time synchronization** between the individual satellites and the GPS receiver
  - Real time update of the exact location of the satellites
  - Precise measurement of the time of flight
  - **Interferences** with other signals

Global Positioning System (GPS) (2)



Global Positioning System (GPS) (3)

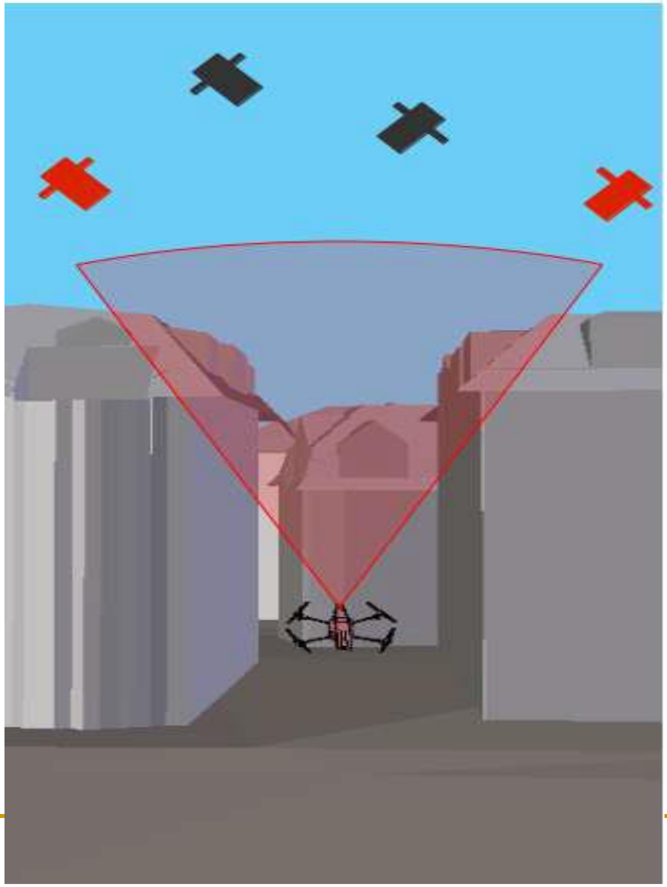
- **Time synchronization**:
  - **atomic clocks on each satellite**
  - monitoring them from different ground stations.
- Ultra-precision time synchronization is extremely important
  - electromagnetic radiation propagates at light speed
- **Light travels roughly 0.3 m per nanosecond**
  - position accuracy proportional to precision of time measurement
- **Real time update of the exact location of the satellites:**
  - monitoring the satellites from a number of widely distributed ground stations
  - master station analyses all the measurements and transmits the actual position to each of the satellites
- **Exact measurement of the time of flight**
  - **quartz clock on the GPS receivers are not very precise**
  - the range measurement with four satellite allows to identify the three values (x, y, z) for the position and the clock correction ΔT
- Commercial GPS receivers have nominal position accuracy of 3 meters

GPS Error Sources

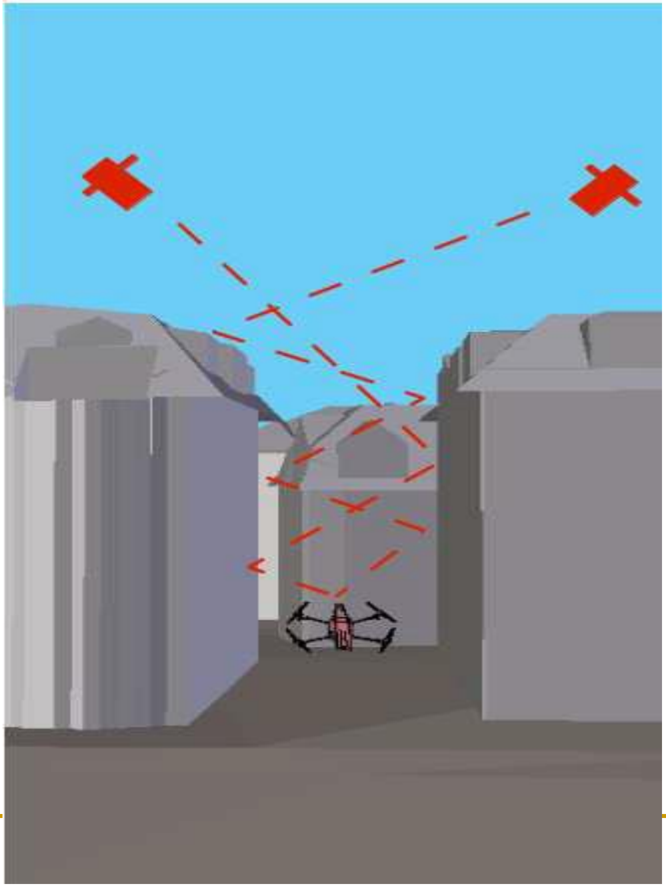
- Ephemeris data errors: **1 meter**
- Tropospheric delays: **1 meter**
  - The troposphere is the lower part (ground level to from 8 to 13 km) of the atmosphere that experiences the changes in temperature, pressure, and humidity associated with weather changes. Complex models of tropospheric delay require estimates or measurements of these parameters.
- Unmodeled ionosphere delays: **10 meters.**
  - The ionosphere is the layer of the atmosphere from 50 to 500 km that consists of ionized air. The transmitted model can only remove about half of the possible 70 ns of delay leaving a ten meter (30 ns) un-modeled residual.
- Multipath: **0.5 - 100 meters**
  - Multipath is caused by reflected signals from surfaces near the receiver that can either interfere with or be mistaken for the signal that follows the straight line path from the satellite. Multipath is difficult to detect and sometime hard to avoid.
- Coverage: Number of satellites under line of sight

Global Positioning System (GPS) (4)

- Satellite coverage

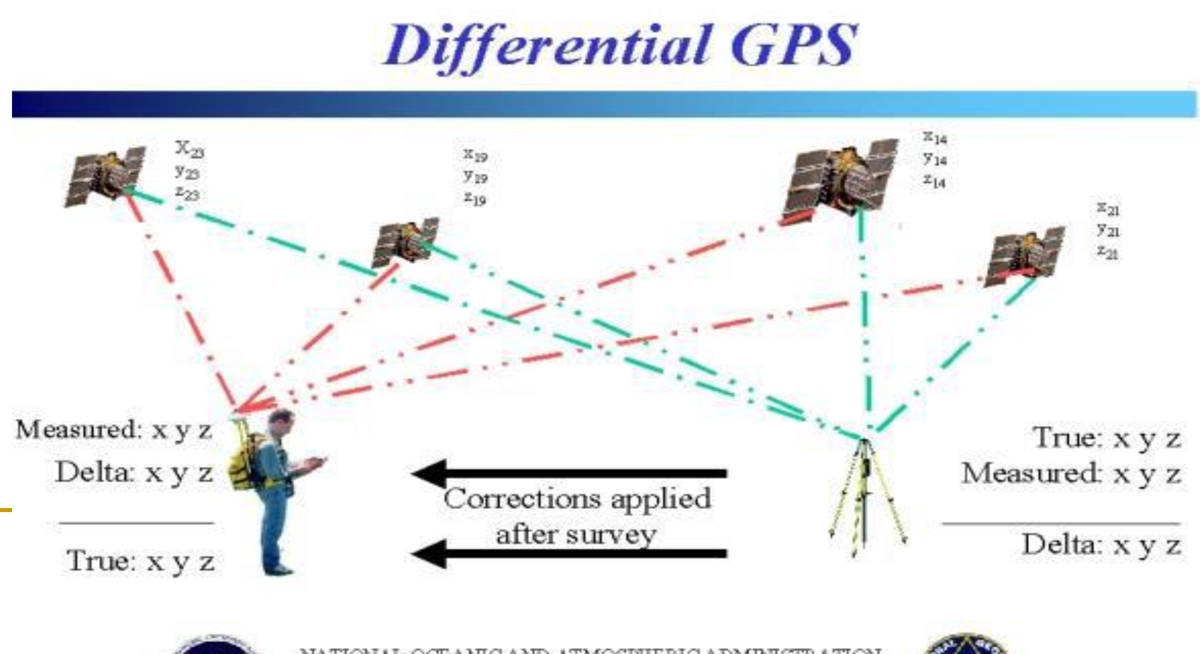


Multipath problem



Differential Global Positioning System (dGPS) (5)

- DGPS requires that a GPS receiver, known as the **base station**, be set up on a **precisely known location.** The base station receiver calculates its position based on satellite signals and compares this location to the known location. The difference is applied to the GPS data recorded by the roving GPS receiver
- **position accuracies in sub-meter to cm range**



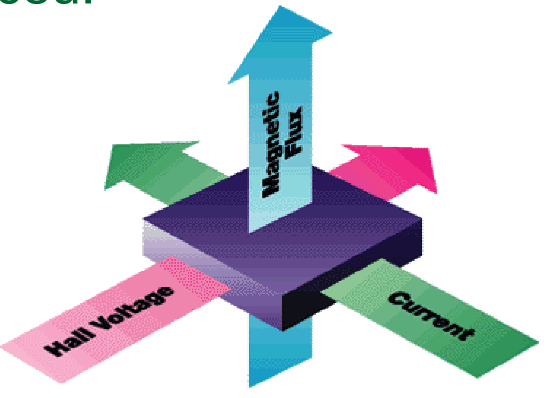
Hall-effect sensor

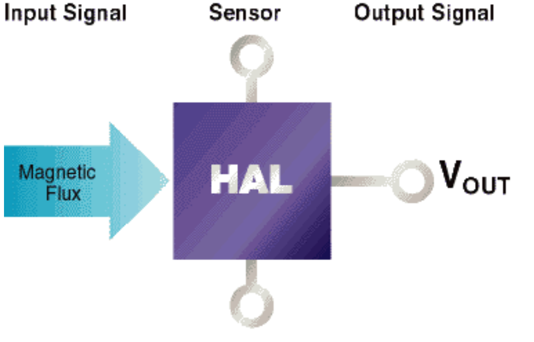
- The change in magnetic field induces a current, the change in intensity and direction of the current can measure the velocity and direction object producing the magnetic field.
- This sensor measures the thickness of nonferrous materials with 1% accuracy by sandwiching the material being measured between a magnetic probe on one side and a small target steel ball on the other side.
- It measures up to 10 mm. The Hall effect sensor is used to measure the magnetic field, as a dc measurement; ac Hall effect measurements can be made more precisely because they eliminate bias and are done with less noise

Hall-effect sensor

- As the magnetic field between the sensor and a metal ball changes the sensor can measure it's proximity and direction by measuring the direction and intensity of the current induced.

- Range of about 6 mm (Mechatronics handbook)
- Works on about 5v-6v and about 4-10 mA
- Temperature: from about -40°C to about 150°C
- Can work as source or sink depending on the type
- Works on proximity to other external magnet.
- Non-contact switching action
- High resolution
- Can produce a digital output





Sensors – Feelers

- Whiskers
  - Wire suspended through conductive “hoop”
  - Deflection causes contact with “hoop”
  - Springy wire that touches studs when deflected
  - Reaches beyond robot a few inches
  - Simple, cheap, binary output

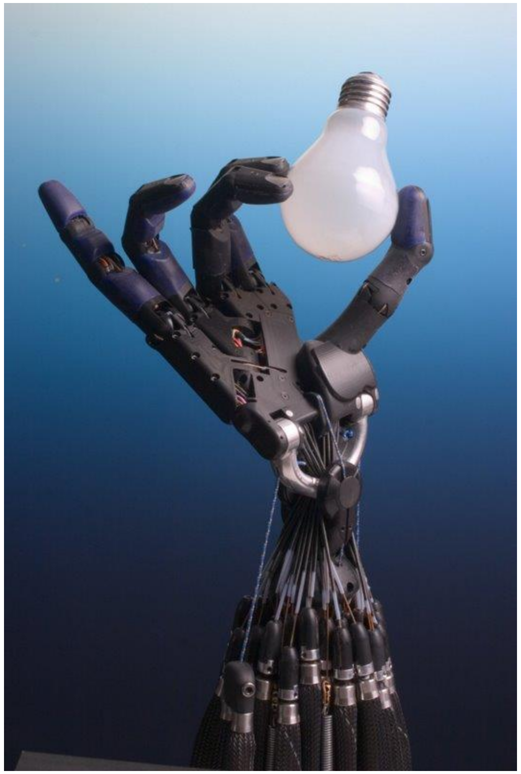
- Bumpers & Guards
  - Impact/Collision sensor, senses pressure/contact
  - Microswitches & wires or framework that moves
  - Simple, cheap, binary output, easy to read

Tactile sensors

- In robotics, they are used in slightly different context:

  Tactile (sensor): “a device that measures parameters of a contact interaction between the device and some physical stimuli” [Nicholls and Lee, 1989]

- Main application areas: cutaneous (skin) sensors, sensing fingers, soft materials, industrial robot grippers, multifingered hands, probes and whiskers, analysis of sensing devices, haptic perception, processing sensory data



Tactile sensing

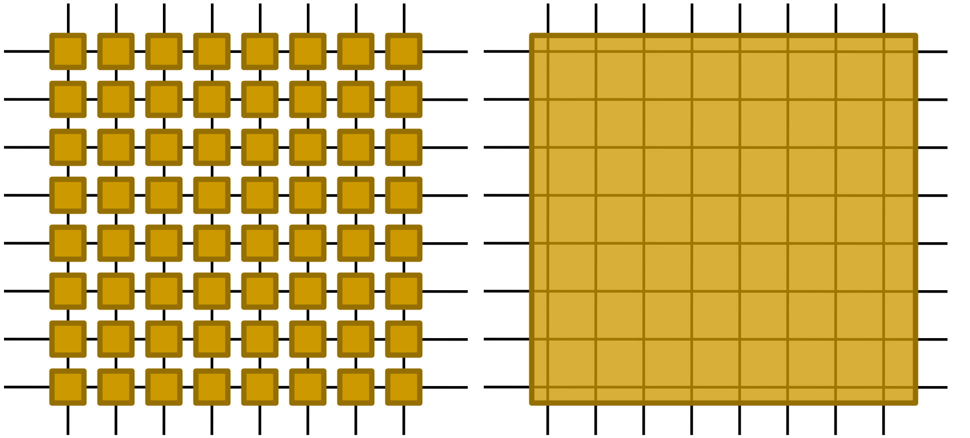
- What is sensed?

  Deformation of bodies (strain) or fields (electric or magnetic).
  - Through deformations, measure change of parameters, and find:
    - Static texture, local compliance, or local shape
    - Force (normal and/or shear) (*indirect*)
    - Pressure
    - Slippage

- Categories of tactile sensing
  - Simple contact
  - Magnitude of force
  - three-dimensional shape
  - Slip
  - Thermal properties

Tactile sensing: Methods of transduction

- Usually an array of discrete sensing elements or a continuous sensitive medium with discrete sampling.
- Sensing elements can be many types:
  - On/Off: a simple switch
  - Resistive: strain gauge, piezoresistive.
  - Capacitive
  - many other methods (magnetic, piezoelectric, thermal)



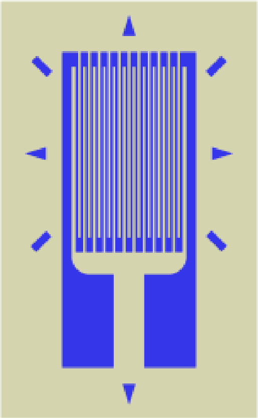
1) Resistance change elements:

- One of the most common.

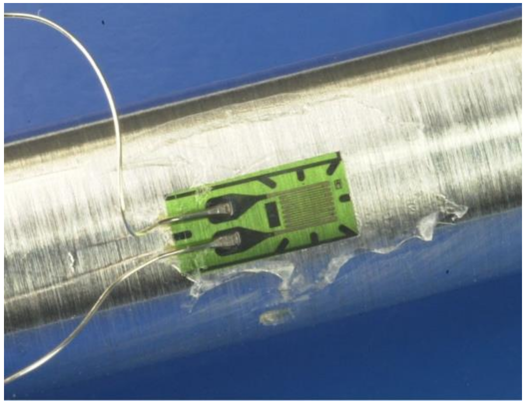
  -Sensing element changes resistance when strained.
- Strain gauge: a thin film with a metal pattern that changes resistance when strained.
- Piezoresistive element.

  Force changes shape = changes resistance

  Resistance change is a result of both geometry change and resistivity change.
- <u>Advantages:</u> very simple, good dynamic range, easy readout, durable,
- <u>Disadvantages:</u> non-linearity, hysteresis, many wires

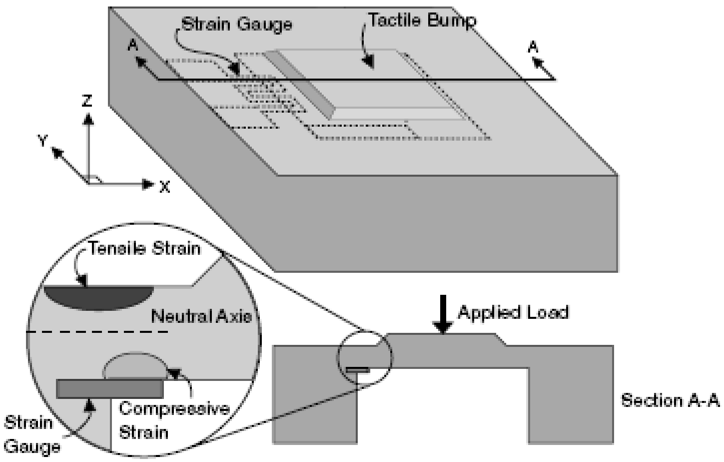


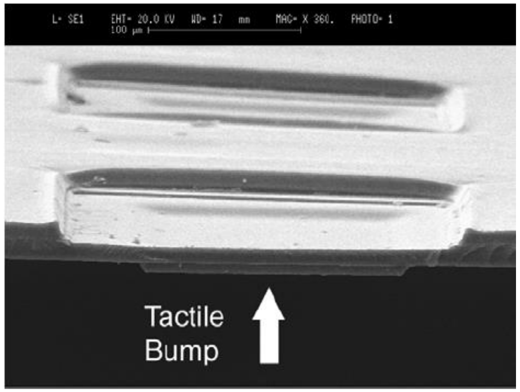
Strain gauge



An example: resistive sensing

- A polyimide based MEMS tactile sensor (10 x 10 array)
  - MEMS diaphragm
  - Strain gauge located where the diaphragm connects to the substrate.
  - 10 µm wide serpentine trace of NiCr in a 100 µm × 100 µm square area.
  - Sensitivity is 0.61 $\Omega\ \mu m^{-1}$, with good linearity ($R^2 = 0.974$).



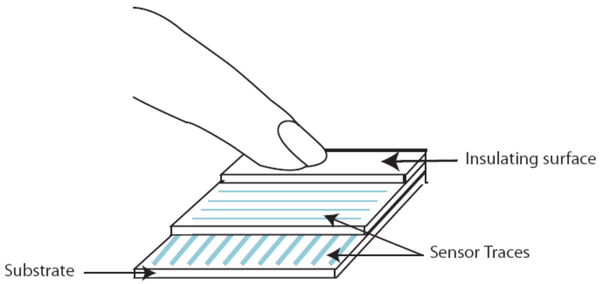


[Engel, *et al.*, “Development of Polyimide Flexible Tactile Sensor Skin”]

2) Capacitance change elements:

- Main application area: touchpad!
- 2 Different sensing methods:
  - Mechanically deform and change the capacitance of parallel conducting plates
  - Or: sense the capacitance change due to stray fields (capacitance is increased)

    Touchpads are tuned to human skin!



http://www.synaptics.com/sites/default/files/Capacitive_Resistive.pdf

- Advantages: good dynamic range, linearity
- Disadvantages: noise, measuring capacitance is hard! (compared to measuring resistance)

http://www.analog.com/static/imported-files/data_sheets/AD7142.pdf

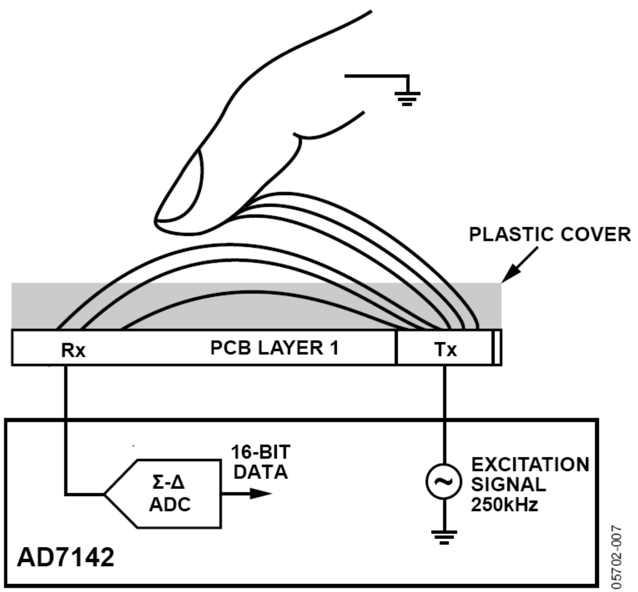
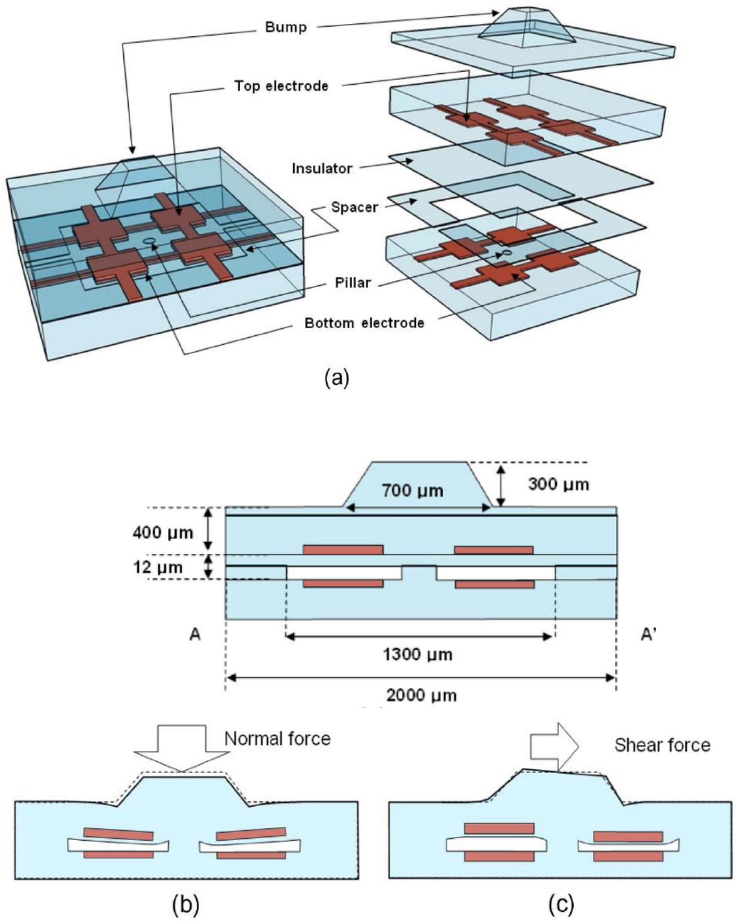


Figure 18. Sensing Capacitance Method

An example: capacitive sensing

- An 8 x 8 array tactile sensor
  - Polydimethylsiloxane (PDMS)
  - Detect force of 10mN, 131kPa in all directions
  - Flexible
  - Sensitivity: 2.5%/mN, 3.0%/mN, and 2.9%/mN for the X, Y, and Z directions, respectively.
  - (why not equal?)



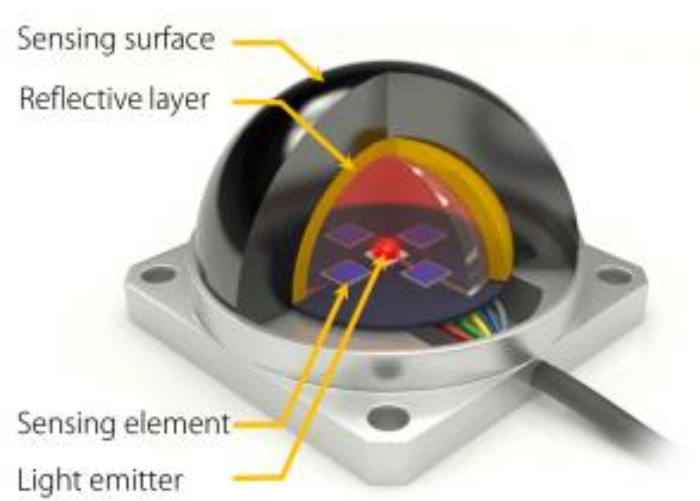
[Lee, *et al.,* “Normal and Shear Force Measurement Using a Flexible Polymer Tactile Sensor With Embedded Multiple Capacitors”]

Tactile sensors – Merits vs. Demerits

Type	Merits	Demerits
Resistive	• Sensitive • Low Cost	• High Power Consumption • Generally detect single contact point • Lack of Contact force measurement
Piezoresistive	• Low cost • Good sensitivity • Low noise • Simple electronics	• Stiff and frail • Non linear response • Hysteresis • Temperature sensitive • Signal drift
Tunnel Effect	• Sensitive • Physically flexibile	• Non Linear response
Capacitive	• Sensitive • Low cost • Availabilityof commercial A/D chips.	• Cross-talk • Hysteresis • Complex Electronics
Optical	• Immunity to electromagnetic Interference • Physically flexible • Sensitive • Fast • No interconnections.	• Bulky • Loss of light by micro bending • Chirping • Power Consumption • Complex computations.
Ultrasonic	• Fast dynamic response • Good force resolution	• Limited utility at low frequency • Complex electronics • Temperature Sensitive
Magnetic	• High sensitivity • good dynamic range, • no mechanical hysteresis • physical robustness	• Suffer from magnetic interference • Complex computations • Somewhat bulky • Power Consumption
Piezoelectric	• Dynamic Response • High Bandwidth	• Temperature Sensitive • Not so robust electrical connection.
Conductive Rubber	• Physically flexible	• Mechanical hysteresis • Non linear response

Lack of solution

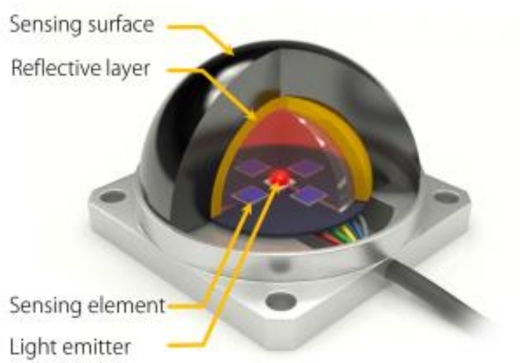
- Sensors:
  - Strain gauge sensors
  - Tactologic grid sensor
- Problems:
  - No 3D
  - Fragile
  - Not available

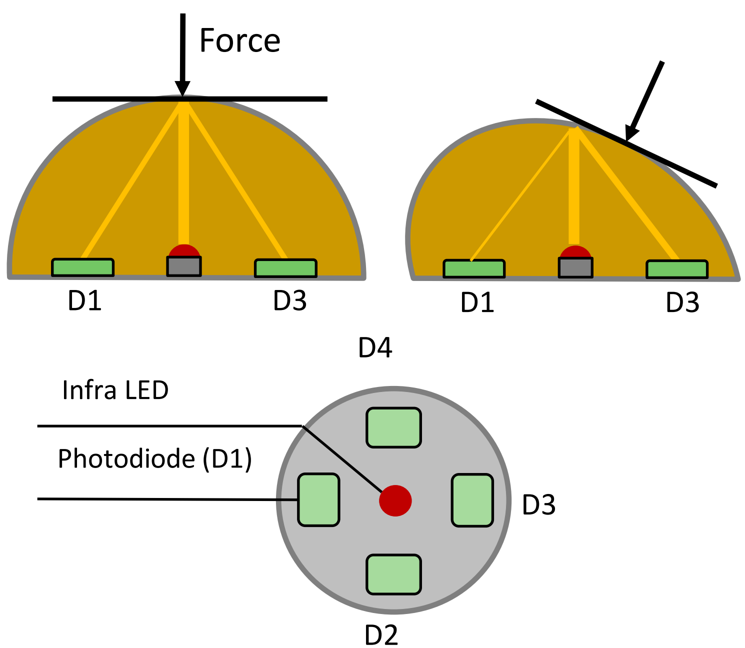


⇨ OptoForce sensor

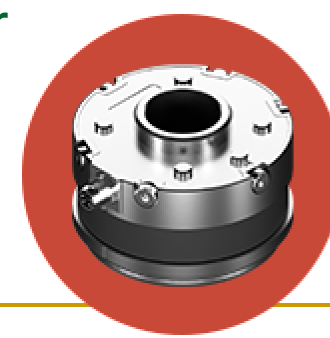
- We designed the sensor based on simple ideas and implemented the first proof-of-concept versions in our Robotlab

Optoforce 3D sensor

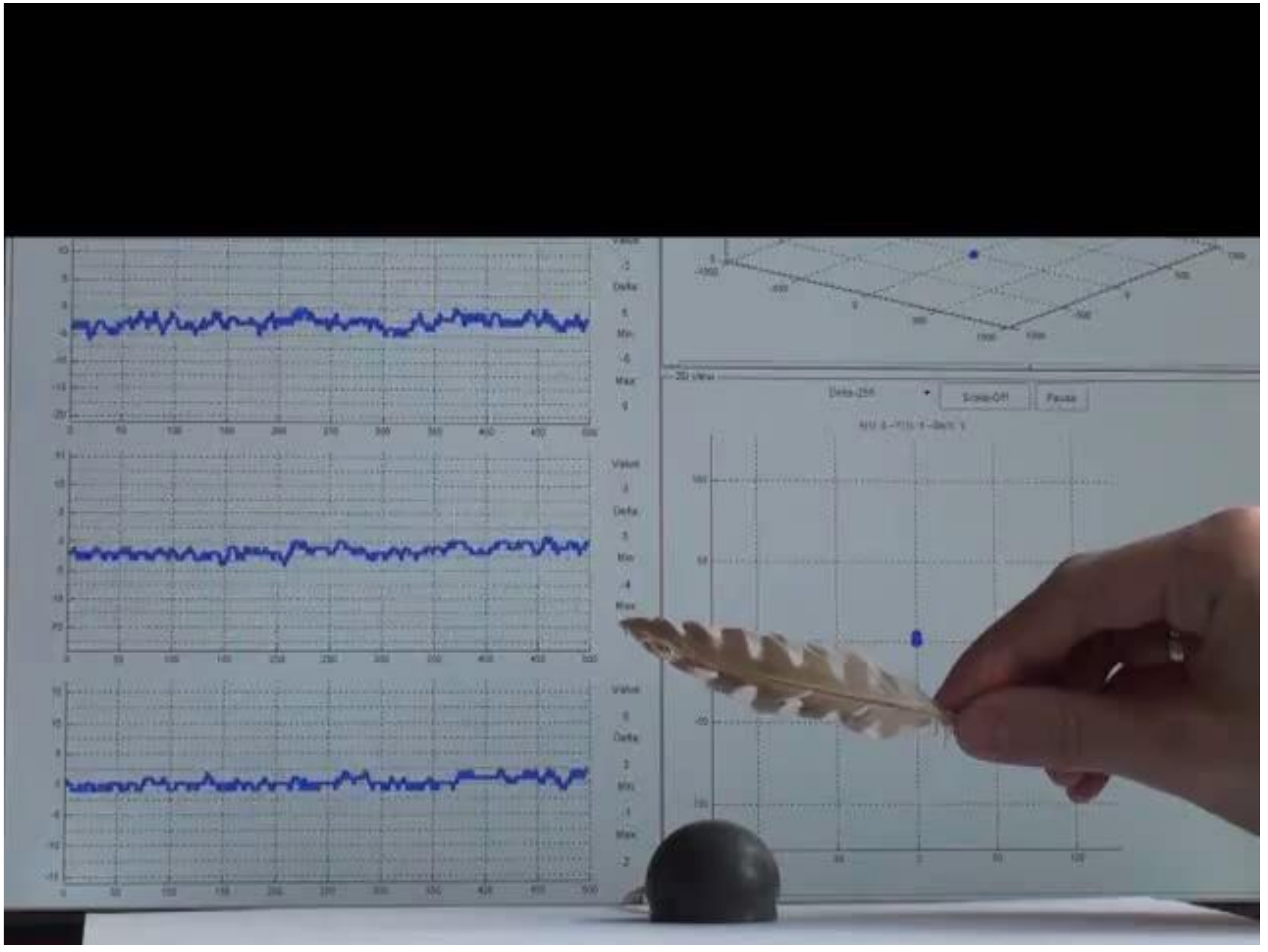




- Multi-axial force sensor
- Unique optical principle
- Silicone rubber based
- Force and direction
- Robust solution – overload
- Low consumption
- High frequency
- 3D force sensor and 6-axis torque sensor



Optoforce sensor



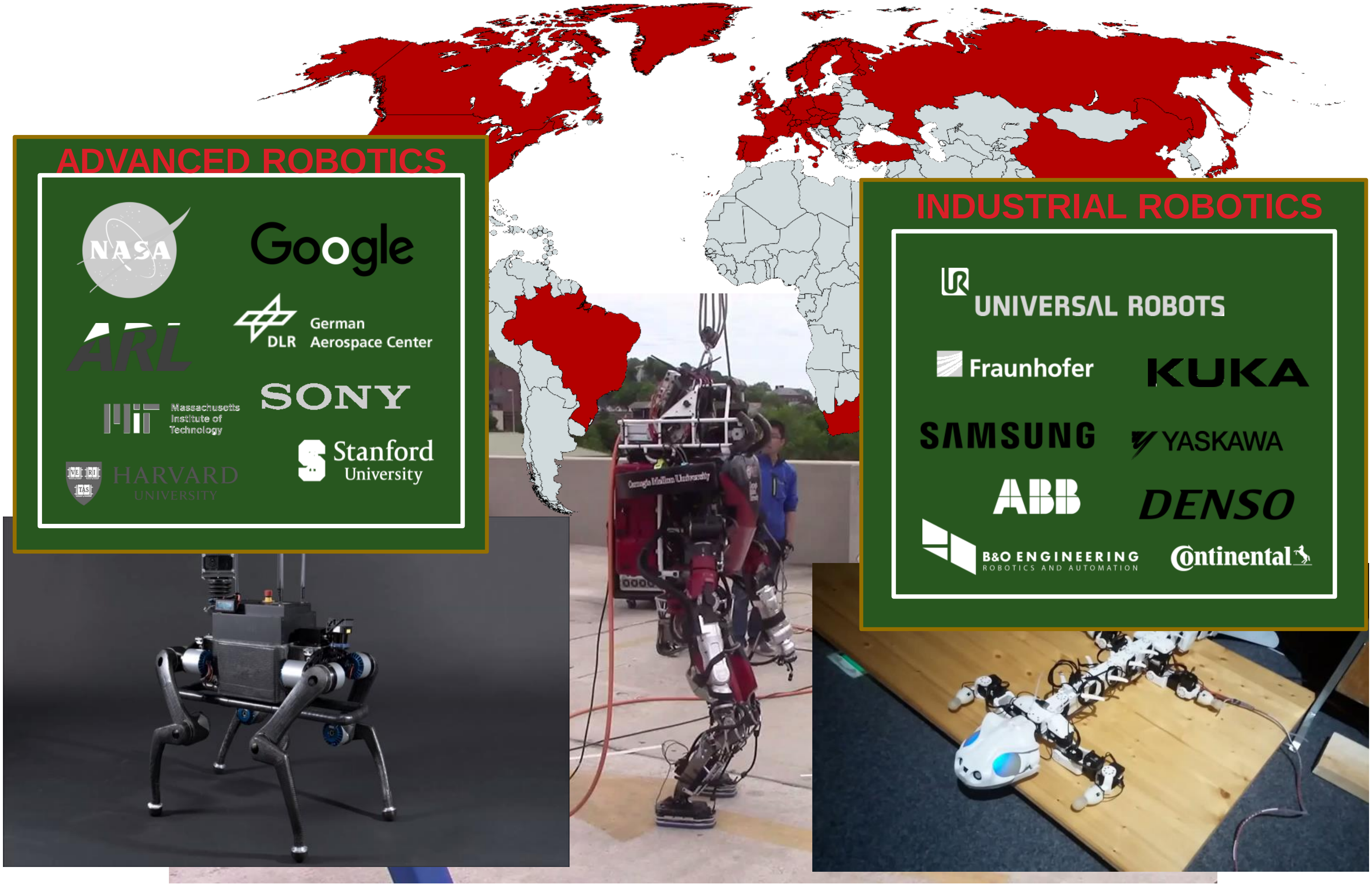
Force sensors – comparison to OF

COMPARISON OF RELEVANT TECHNOLOGIES

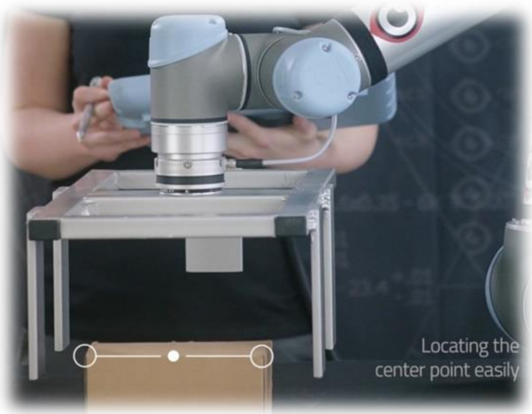
●●●●●	Best
●●●●○	Better
●●●○○	Normal
●●○○○	Worse
●○○○○	Worst

	Load-cells	Foil-type	Piezoelectric-type	OPTOFORCE
Operating Temperature (with temperature compensation)	●●●○○	●●○○○	●●●○○	●●●●●
Force Range (available measurement ranges)	●●●●●	●○○○○	●●●●●	●●●●●
Calibration requirement (complexity of the procedure)	●●●●○	●●●○○	●●●●○	●●●●○
Overall Size (for sensor and required electronics)	●●●○○	●●●●●	●●●●○	●●●●○
Power Consumption (for sensor and required electronics)	●●●○○	●●●●○	●●●○○	●●●●●
Service Life (expected lifetime without any failure)	●●●●○	●●○○○	●●●●○	●●●●○
Diagnostic Feature (ability to validate the measurement)	●●●○○	●●●○○	●●●○○	●●●○○
Robustness (overload and shock survivability)	●●○○○	●○○○○	●●○○○	●●●●●
Water Resisitivity (capability to work in harsh environment)	●●○○○	●●○○○	●●○○○	●●●●●
Complexity (of sensors and conditioning electronics)	●●●○○	●●●●○	●●○○○	●●●●●
Multi-axis (capability of easy 3D measurement)	●●●○○	●○○○○	●●●○○	●●●●●

Research and development



Industrial applications



center point location

grinding

trajectory setup

box insertion

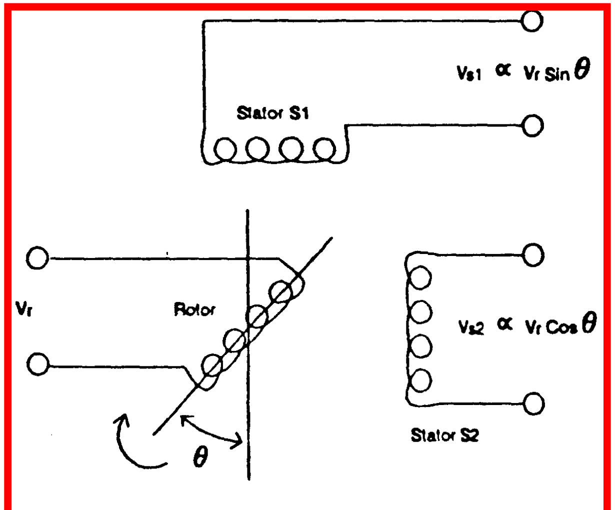
pin insertion

Kinesethic Sensing

- These sensors provide feedback information to the joint/link controllers (servo information)
- They use analog or digital informational responses
- We will explore 3 generally used types:
  - Resolvers
  - Absolute Encoders
  - Incremental Encoders

Resolvers

- Operating principle is that a charged rotating shaft will induce voltage on stationary coils
- Secondary Voltages are related to Primary voltage as Sin and Cos ratios of the primary field voltage

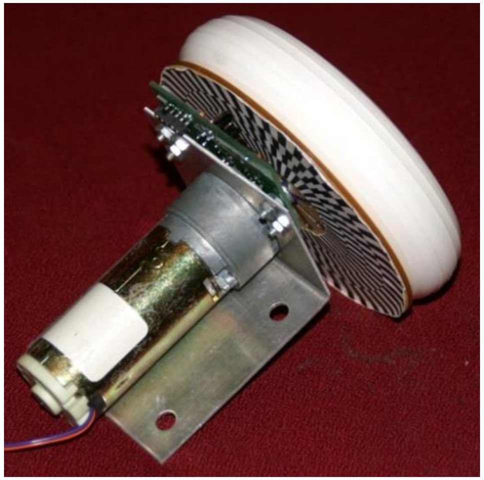


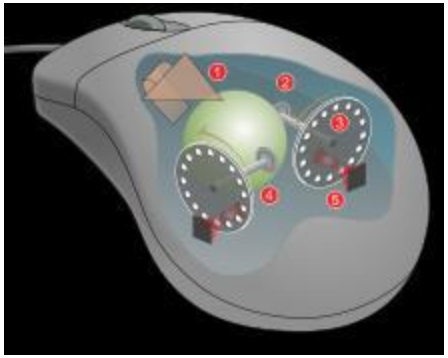
Resolver Schematic Diagram

- These devices are susceptible to Electrical Noise – must be highly shielded
- Usually use gearing to improve resolution
- Typically are expensive but very rugged for use in harsh “shock motion” environments

Encoders

- Definition:
- **electro-mechanical device** that converts linear or angular position of a shaft to an analog or digital signal, making it a linear/anglular transducer





Wheel/motor encoders

- Use cases
  - **measure position** or speed of the wheels or steering
  - **integrate wheel movements** to get an estimate of the position -> odometry
  - optical encoders are proprioceptive sensors
  - typical resolutions: 64 - 2048 increments per revolution.
  - for high resolution: interpolation
- Working principle of optical encoders
  - regular: counts the number of transitions but cannot tell the direction of motion
  - quadrature: uses two sensors in quadrature-phase shift. The ordering of which wave produces a rising edge first tells the direction of motion. Additionally, resolution is 4 times bigger
  - a single slot in the outer track generates a reference pulse per revolution

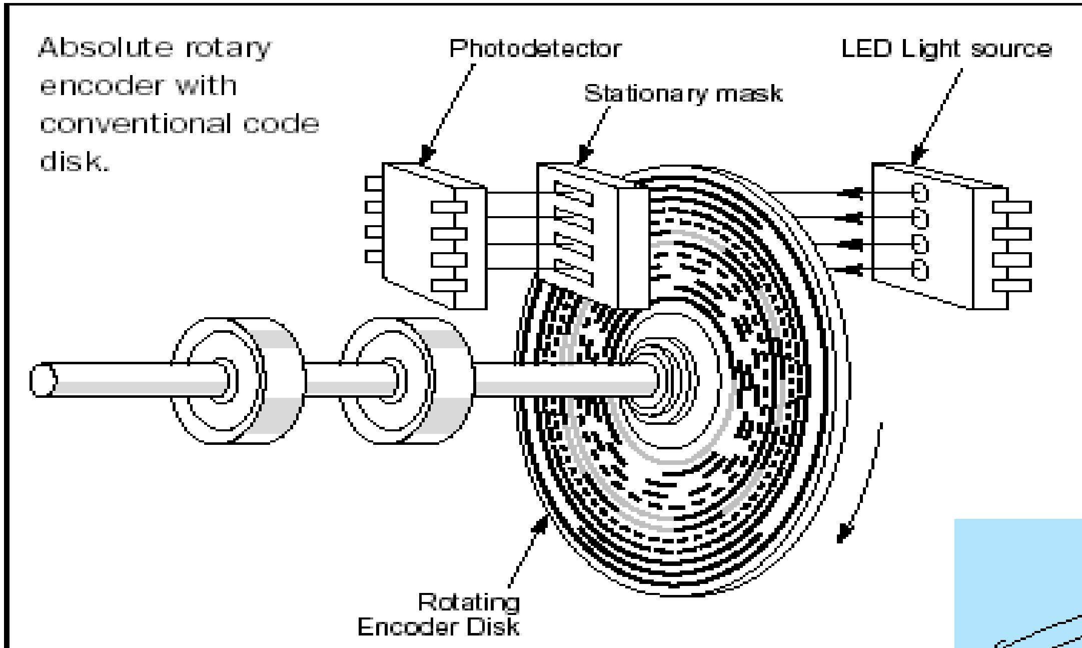
Optical Encoder Positional Sensors

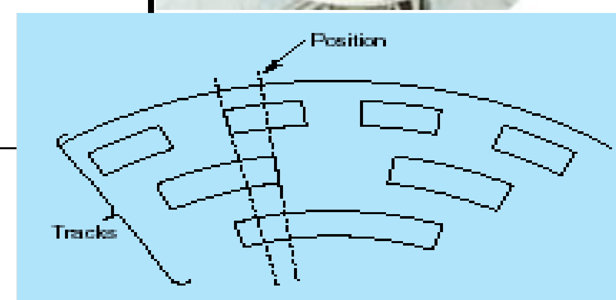
- Based on Photoelectric source/receiver pairs
- Looks for change of state as changing receiver signal level (binary switching)
- Uses a carefully designed disk with clear and opaque patches to control light falling on a fixed sensor as disk rotates
- Can be made ‘absolute’ with several pairs of emitters/receivers or Incremental with 2 ‘out of phase’ photosensors

Optical Servo Measurement Systems

- Absolute Encoders
  - Use Glass Disk marked for positional resolution
  - Read digital words (0010111011) at receiver to represent shaft position
  - Commonly Available with up to 16 bits of information (2^{16}) to convert into positional resolution

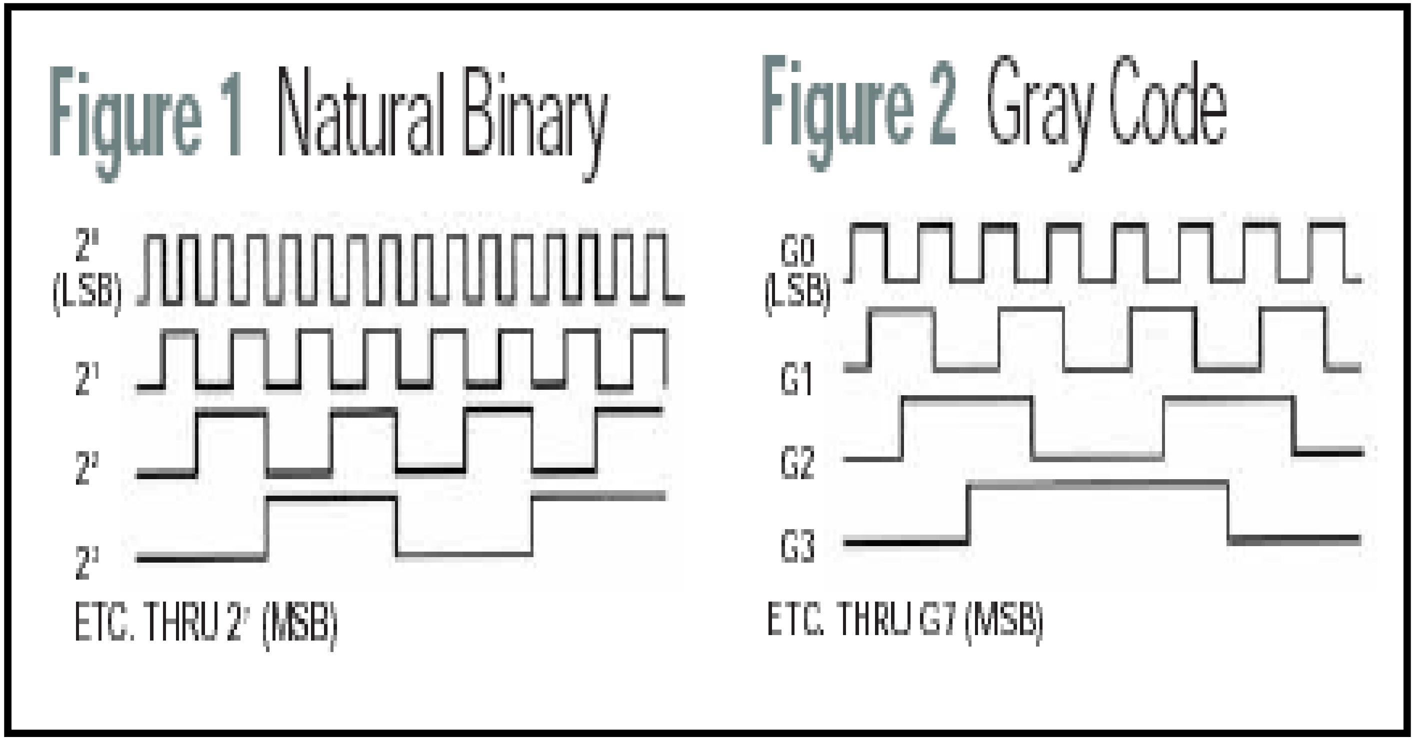
Operating Principle





Typical disk pattern showing radial
scanning method used to read position

Absolute Encoder Variations – 8bit



Comparing Natural Binary to Gray Code

- Natural Binary give actual position when read
  - Actual position is known w/o analysis
- Gray code is designed so only one bit changes “at a time”
  - Where Bit change is subject to positional errors as light “bleeds” around patch edges
- Gray codes are, therefore, less error prone, but require an ‘intelligent converter’ to give actual shaft position

Using Absolute Encoders Resolution:

$$\phi_{ABS} = \frac{360°}{2^n}$$

here: **n is # of 'lines' on disk**

Determine resolution if n = 5?

φ_{ABS} for '5 liner' = $360/2^5$
= 360/32 = 11.25°

- Add Gearing to shaft/encoder coupling
  - New Resolution is:

$$\phi_{ABS} = \frac{360^{\circ}}{\gamma \cdot 2^n}$$

γ **is gear ratio on encoder shaft**

- Increase # of Lines – this increases complexity and cost of the encoder (can be a significant cost increase)

Absolute Encoder for 0.18° Resolution

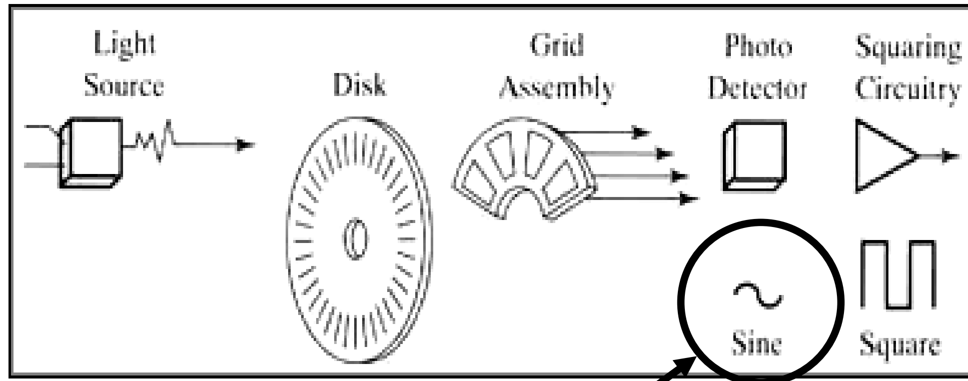
$$\phi_{ABS} = 0.18^\circ = \frac{360^\circ}{2^n}$$

$$n = \log\left(360^\circ / 0.18^\circ \right) / \log 2$$

$$n = 3.301 / 0.301 = 10.965 \rightarrow 11 bits$$

Incremental Encoders

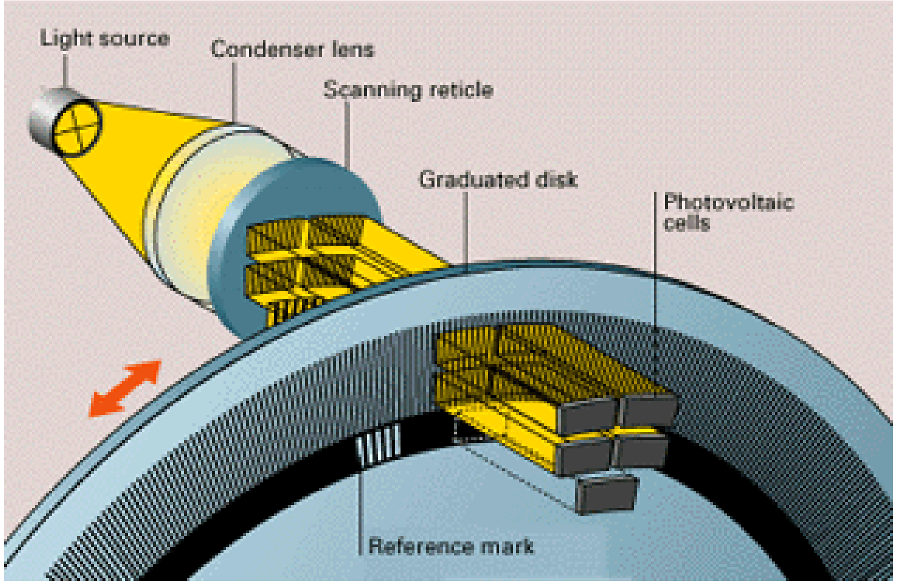
- This devices use 3 pairs of Emitter/receivers
- Two are for positional resolution, the third is a ‘calibrator’ marking rotational start point



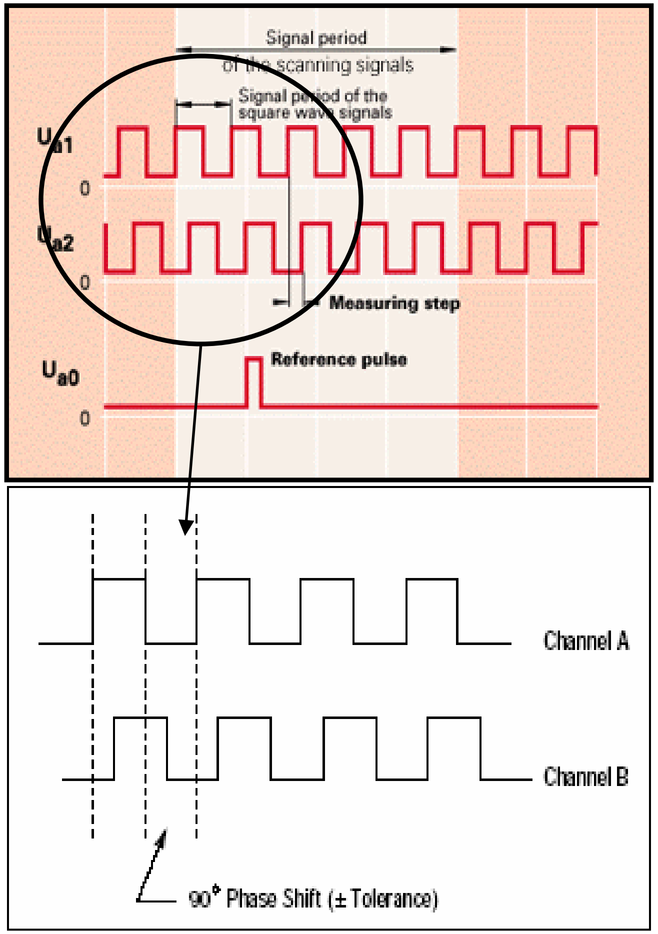
Sine wave is observed due to leakage (light bleeding) around opaque patches!

Incremental Encoders

- The positional detector uses what is called “Quadrature” techniques to look at the changing state of the 2-bits reporting position for each opaque/clear patch on the optical disk



Incremental Encoders



- Notice the "square wave" quadrature signals
  - they are offset by "½ phase"
- Each patch resolves into 2^2 or 4 positions!
- Without hardware change, resolution is a function of the number of patches – or lines

Incremental Encoders

$$\phi_{INC} = \frac{360^\circ}{C_{patch} \cdot 2^2} = \frac{360^\circ}{4C_{patch}}$$

Consider a 500 ‘Line’ incremental encoder?

For 500 line Inc. encoders,
resolution = .18° (w/o gearing)

Comparing Absolute and Incremental Encorders:

- Incremental are *usually* cheaper for same level of resolution
- Absolute are able to provide positional information at any time under power
  - Incremental must be homed after power loss to recalibrate count numbers
- Compared to resolvers, encoders are fragile so must be shock protected during operation

Temporal hypersensing - hyperacuity

- Essentially, it means that the sensitivity and resolution of our senses are generally much higher than that the selectivity of each receptor would allow.
- The key to the mechanism is the use of **sensor arrays**. That is, in the organs, many receptor cells are located and not only by perceiving their function, but by their interconnections and structure they also **perform fundamental processing**.
- Biological research of hypersensitivity often focuses on experiments with a pearl owl (Tyto Alba). The owl has a remarkably good hearing: it is able to catch mice based on the direction of heard sounds. The pearl owl captures its victim in full darkness, relying solely on hearing. Localization can be performed at 1-2 ° angle and can detect several times ten microseconds of interfacial time difference (ITD, arrival time difference between the two ears of the same sound).

Temporal hypersensitivity

- How can the owl detect a few times ten microseconds of time difference when a single action potential has a considerable length of at least 1000 microseconds?
- This question relates to the fundamental operation of the owl sound localization system and includes a certain type of hypersensitivity: namely, **the entire sound localization system can detect a smaller time difference between incoming tones than individual cells** because the action potentials are relatively slower. So here it is a temporal hypersensitivity or hyperacuity.

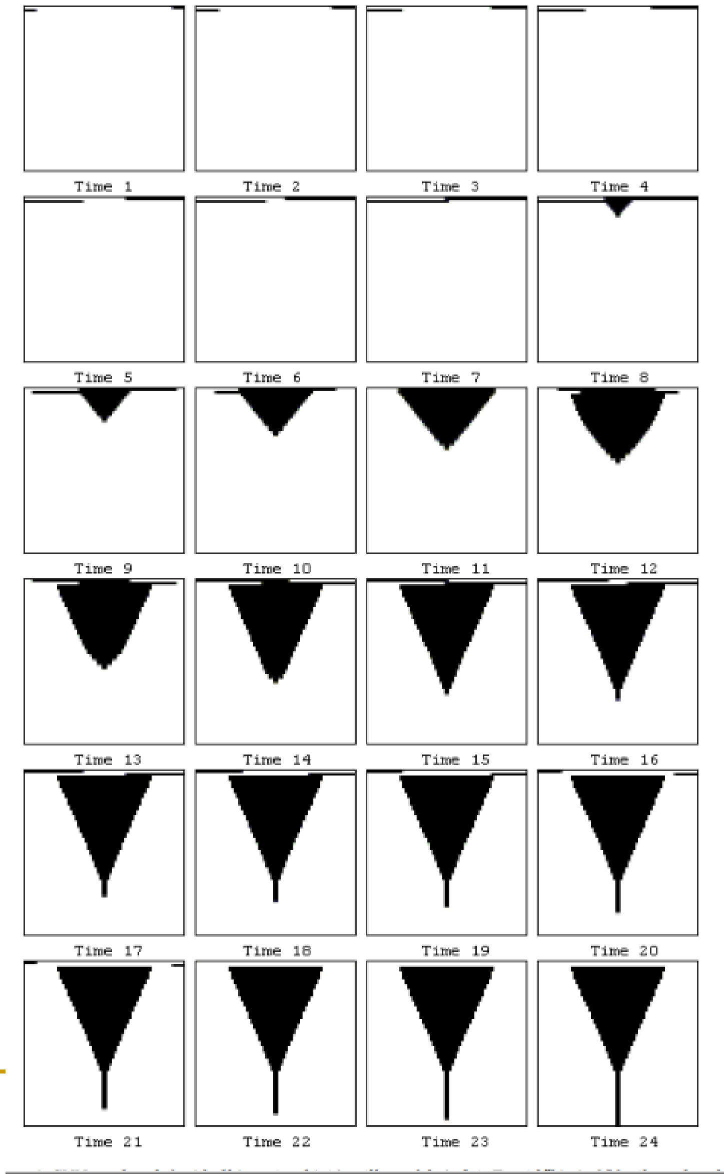
Requirements of hypersensitivity

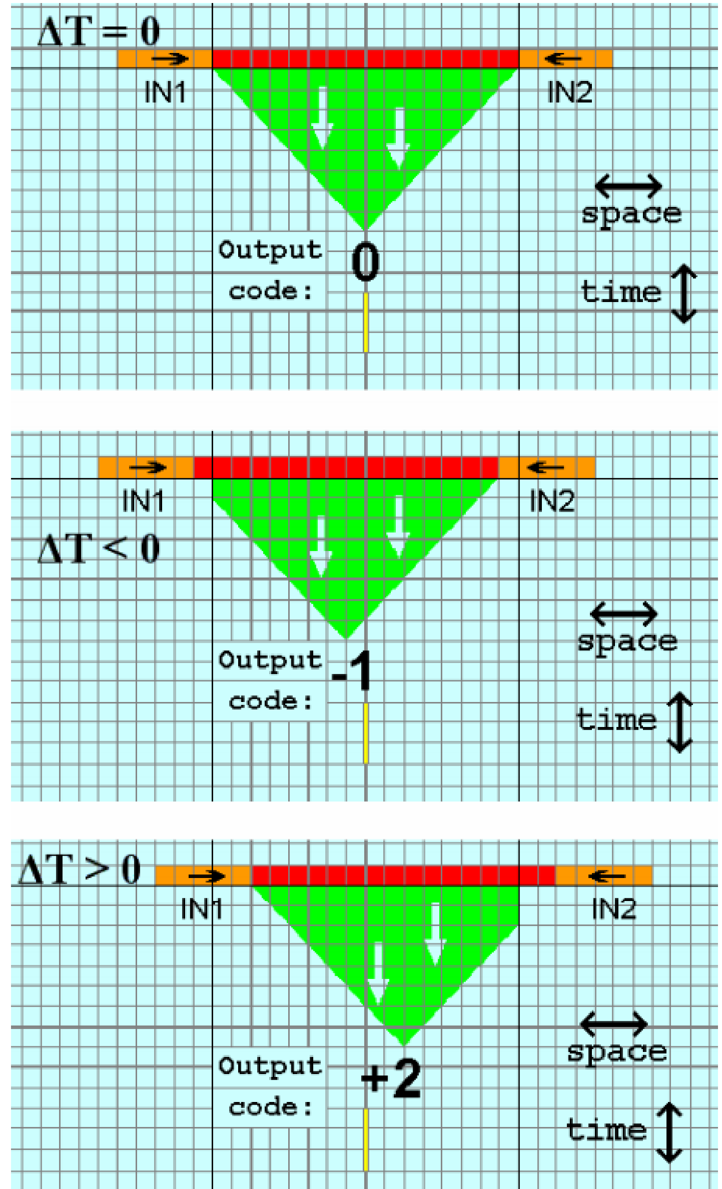
- In biology there are several examples for this neural structure: pearl owl, bat, electric fish. Summarizing the scientific results we can state that the following structural conditions are required for this hyper-precision:
  - Receptor-array or sensor array
  - Overlap between individual receptive fields
  - Lateral interaction between the receptors, or between the synaptic and topographic processing areas

Requirements of hypersensitivity

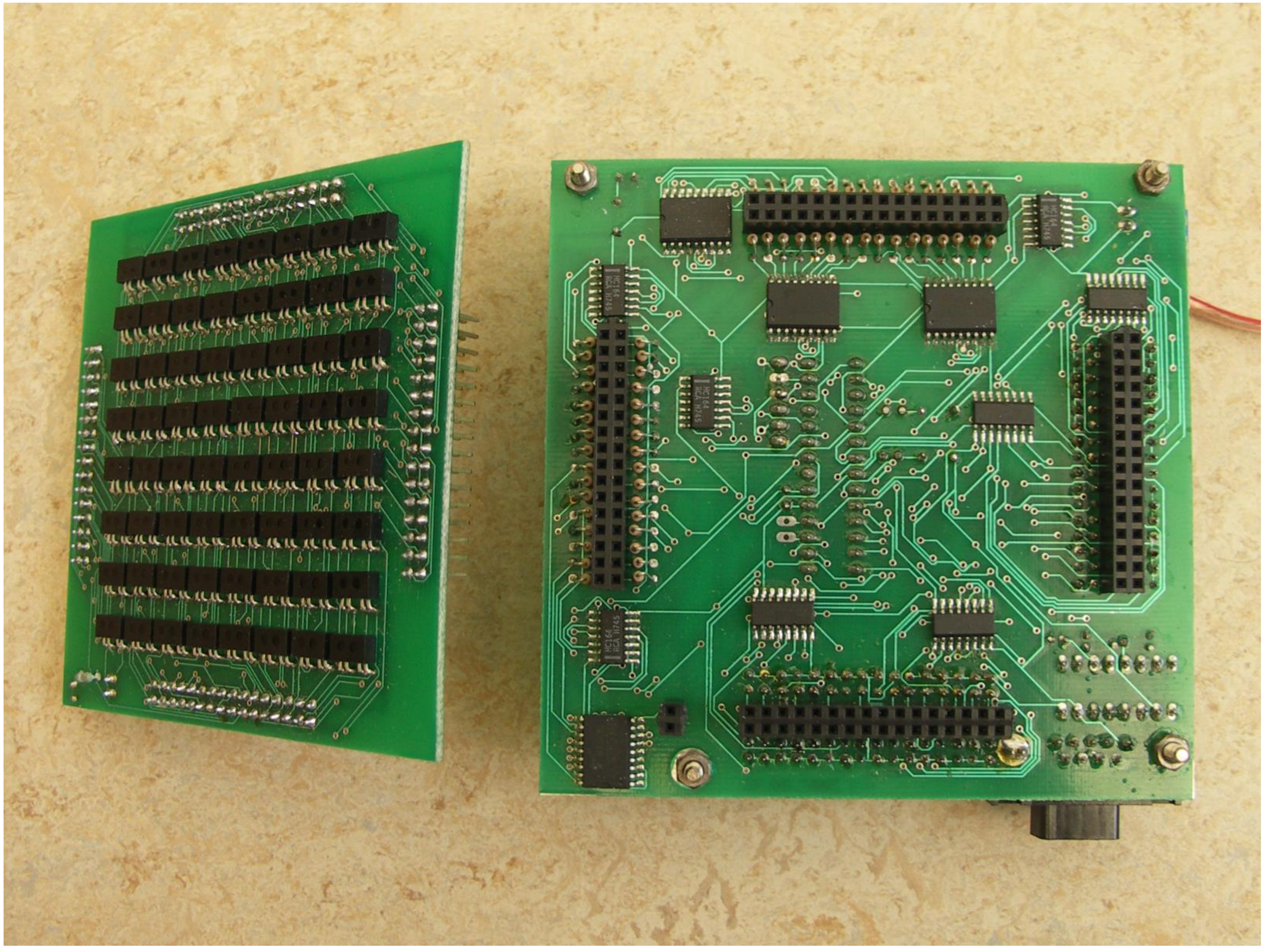
- Hypersensitivity is a phenomenon that maps a stimulus value to a group of nerve cells. It creates a spatial map where different stimuli (e.g. the direction of the heard sound) activates different nerve cells.
- The hypersensitive structure can be divided into three parts:
  - I. Broadly tuned receptive cells with low selectivity (broadly tuned receivers)
  - II. Increasing contrast, increasing sensitivity in multi-steps, foreward-excitation - backward-inhibition synaptic structures. (spatial contrast enhancement)
  - III. Creating a final stimulus map (topographical neuronal map)

TDC time measurement - Hyperacuity

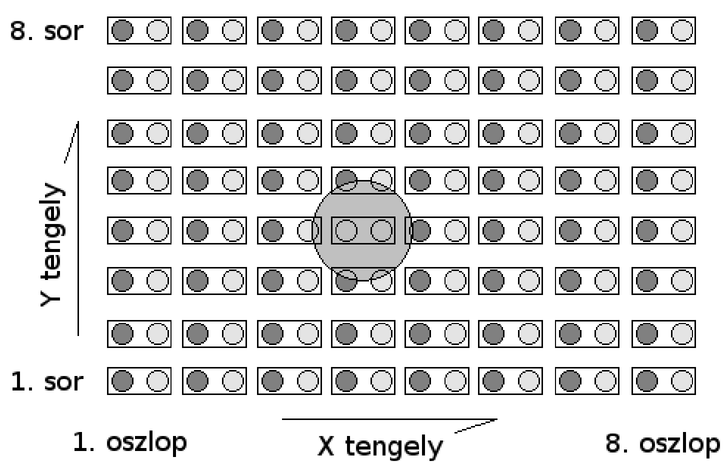


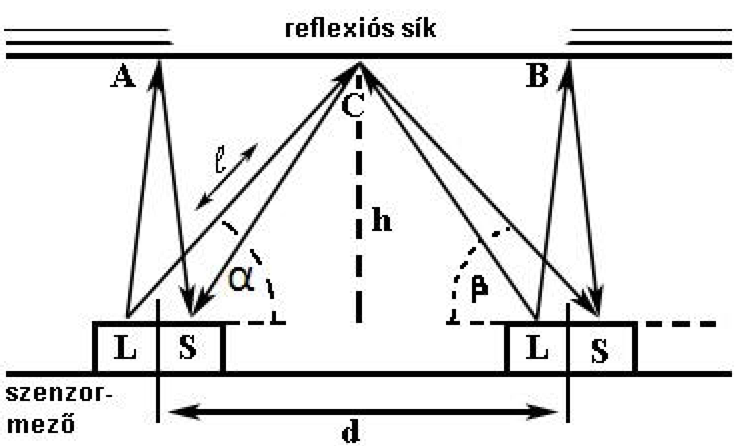


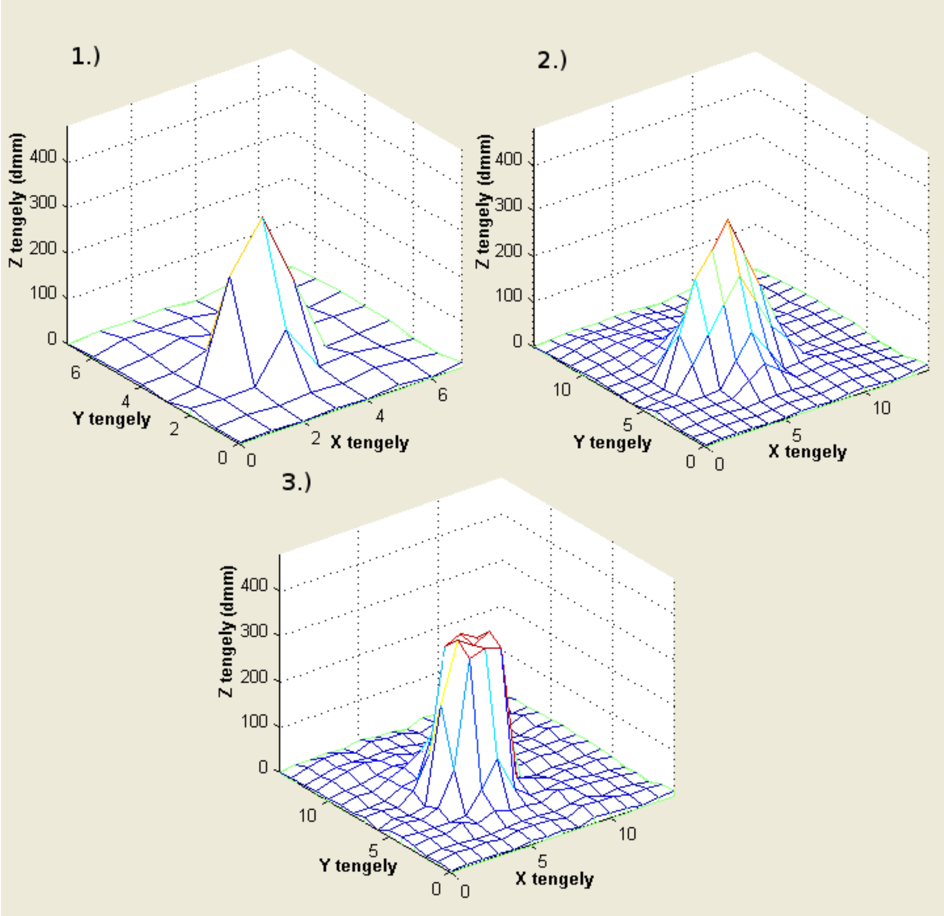
Infra sensor array



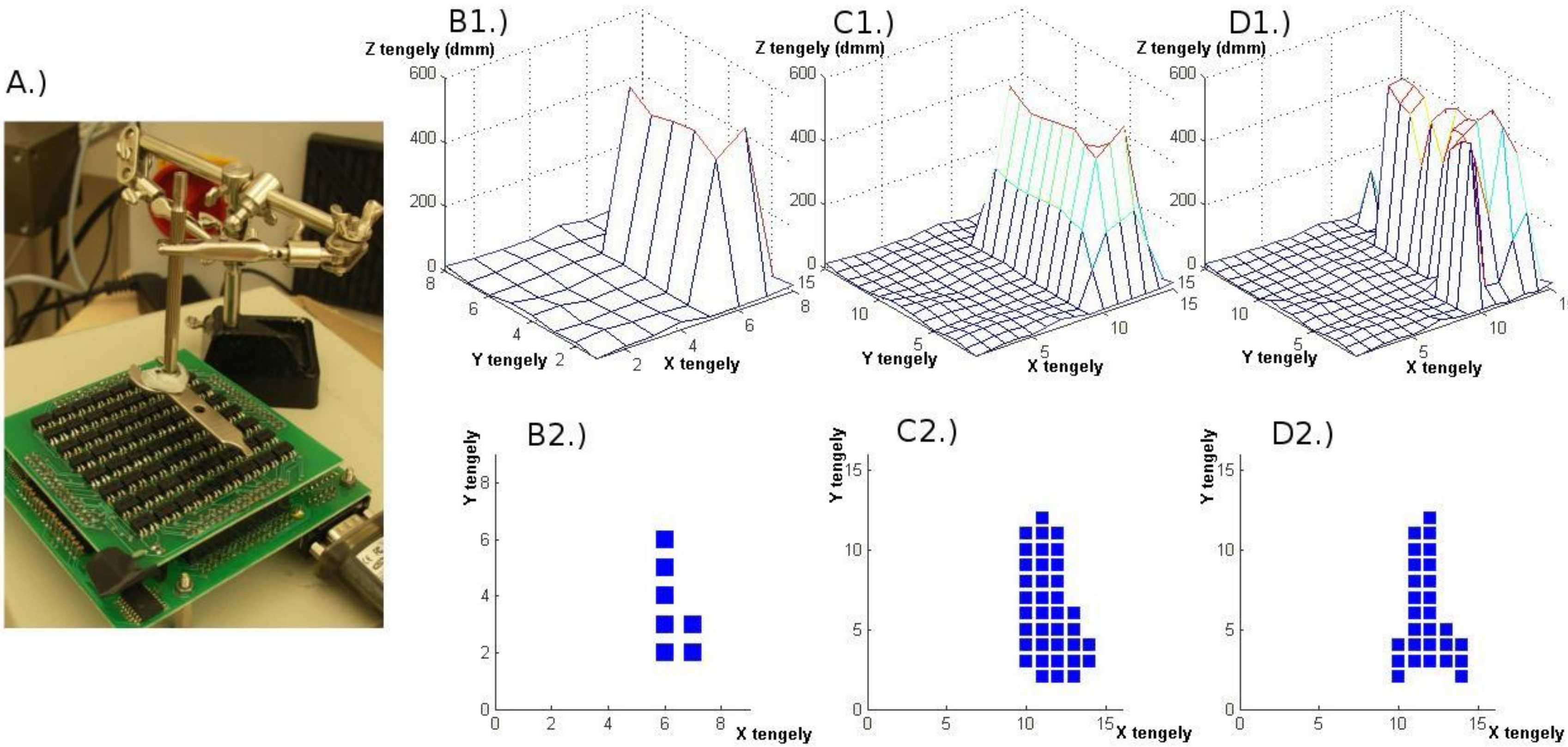
Infra sensor array – passive measurement



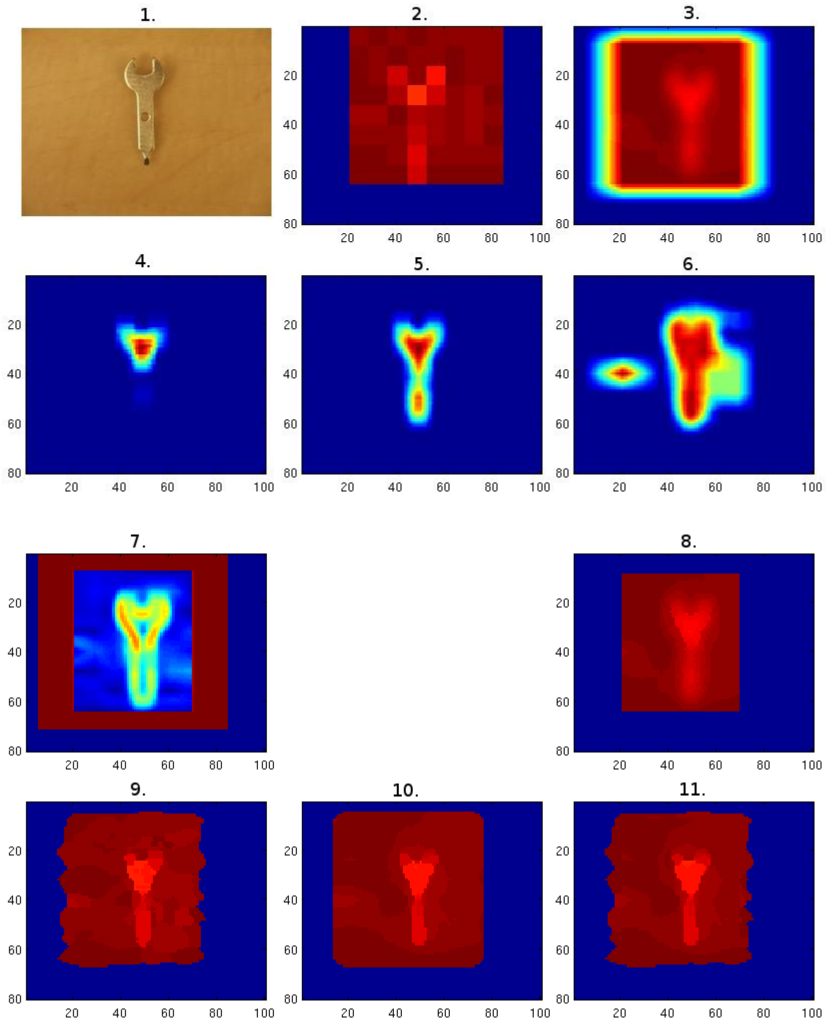


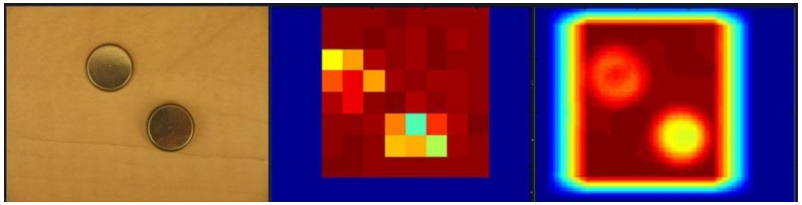


Infra sensor array – passive measurement

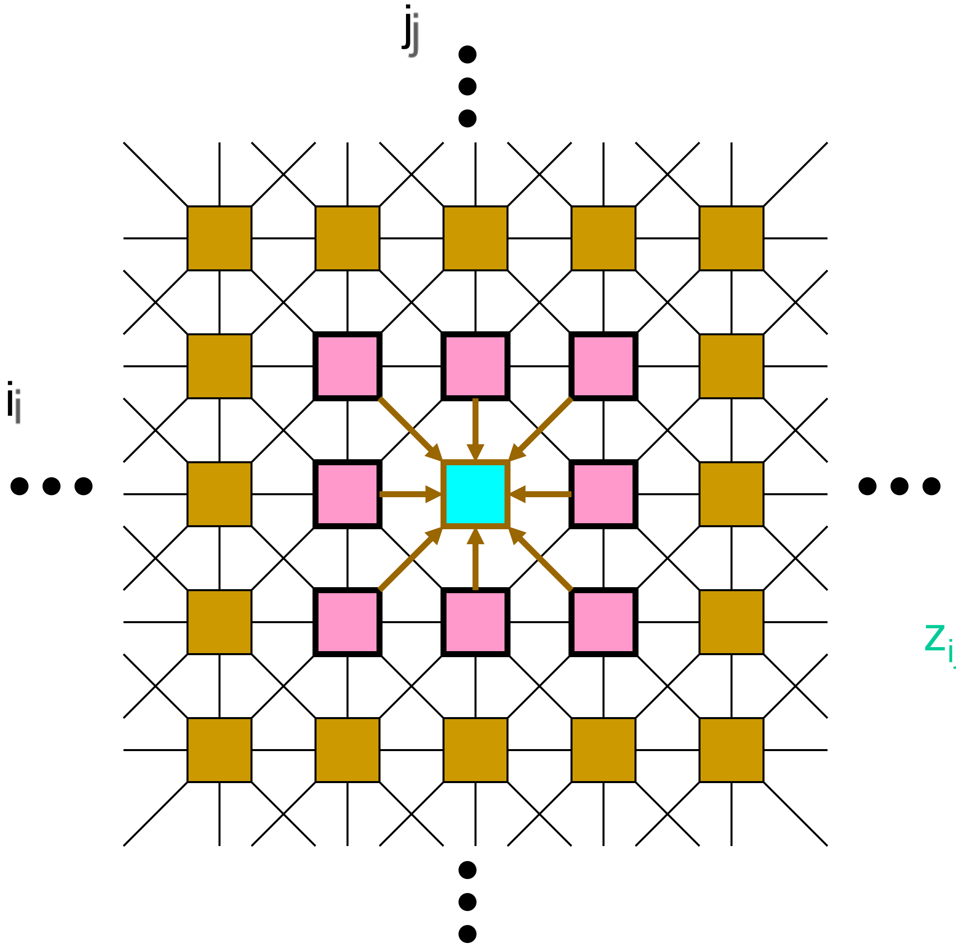


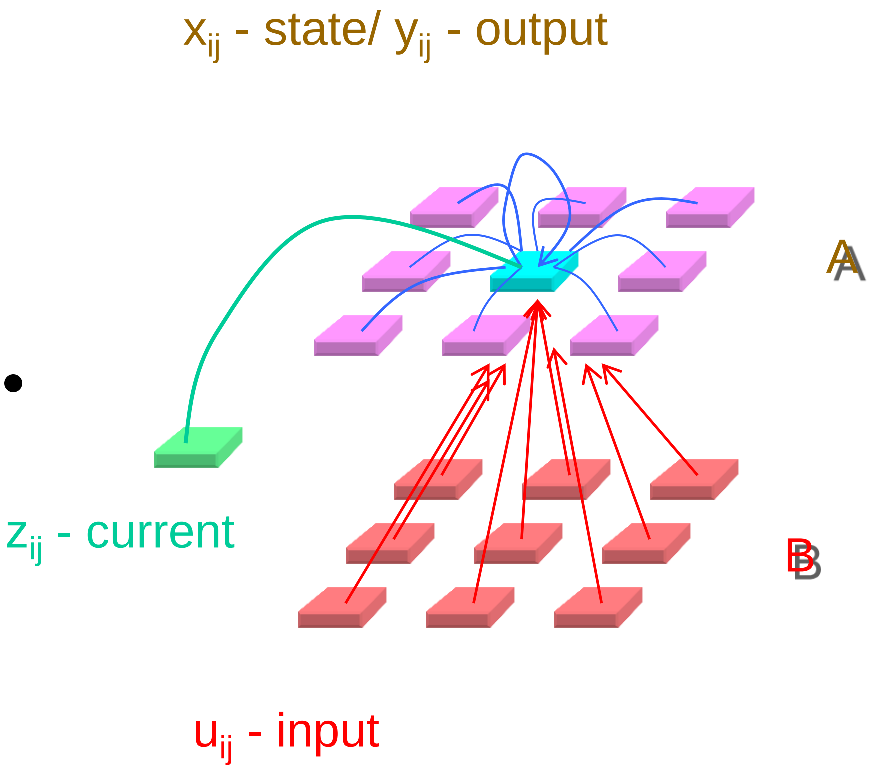
Infra sensor array – active measurement



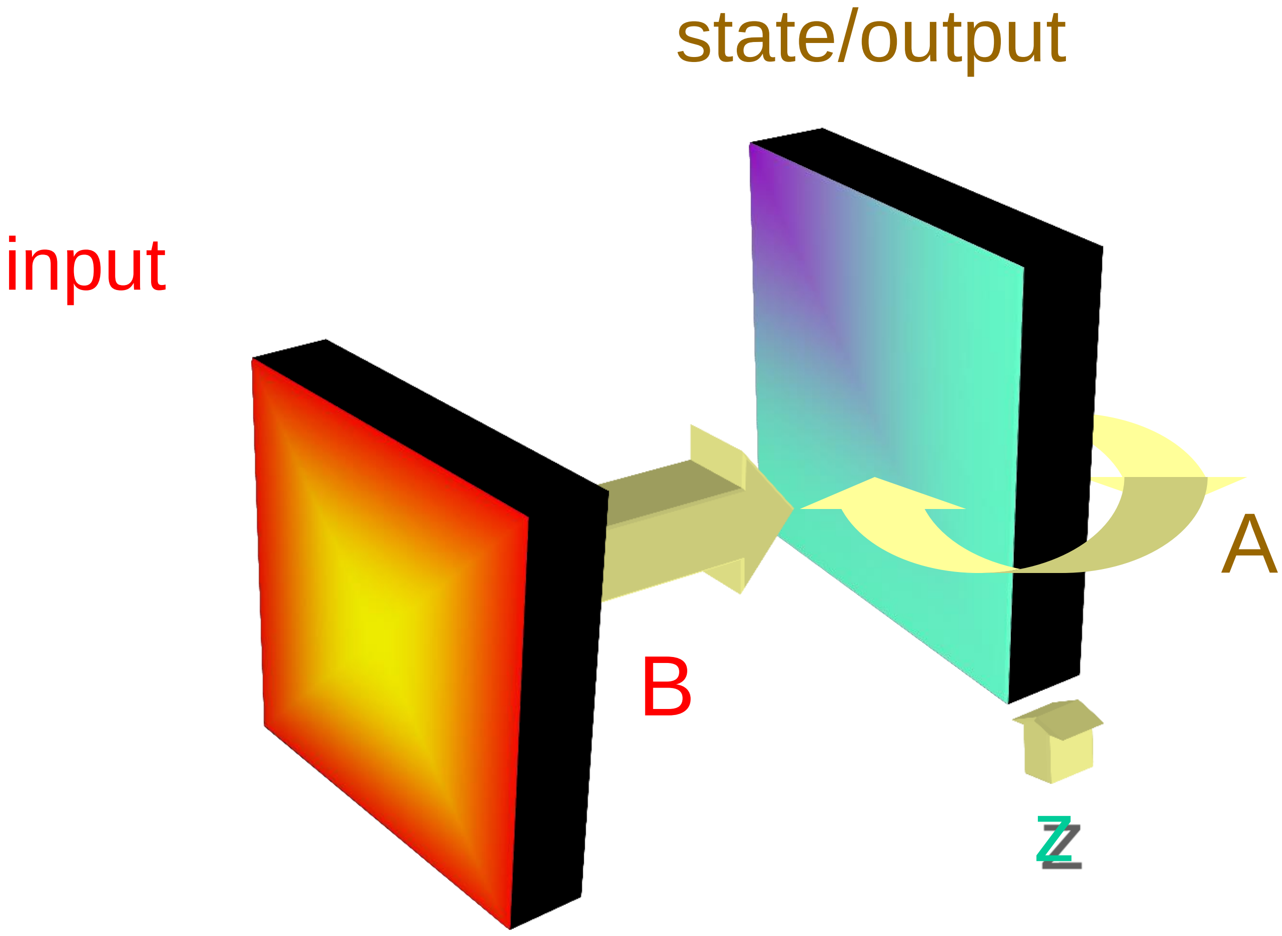


Cellular Neural Network(CNN)

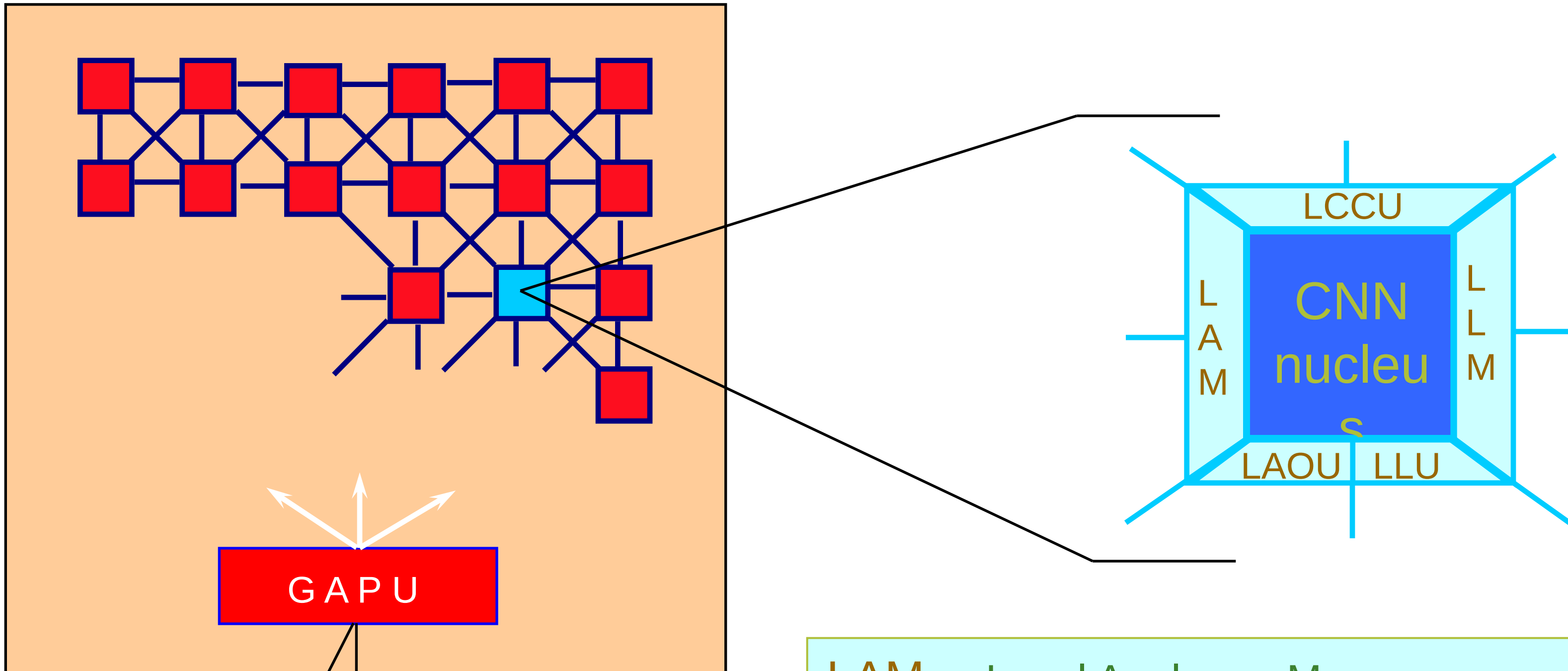




CNN computing



CNN universal machine



GAPU: Global Analogic Programming Unit

LAM: Local Analogue Memory
LLM: Local Logic Memory
LCCU: Local Communication and Control Unit
LAOU: Local Analogue Output Unit
LLU: Local Logic Unit

APR: Analog Instruction Register
LPR: Logic Program Register
SCR: Switch Configuration Register
GACU: Global Analogic Control Unit

$[A_1\ B_1\ z_1], [A_2\ B_2\ z_2], \ldots$

"Analogic algorithms"

End of Lecture 07.

i.) Sensors for localization and navigation
ii.) Collision, touch, pressure, force and temperature sensing
iii.) Sensing the inner state

György Cserey
04.12.2021.