Mobility & Robotic Sensors

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Outline

- Review of Robot Mobility
- Wheeled Robots
- Sensors & Perception

Mobile Robots

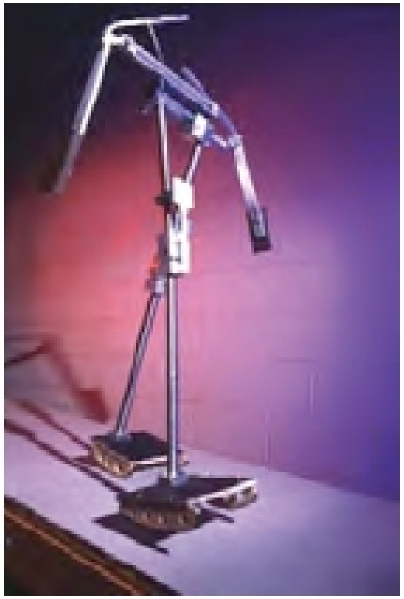
- Ground Vehicles
- Air Vehicles
- Space Vehicles
- Sea and Undersea Vehicles
- Personal Assistance
- Games and Toys

DARPA Grand Challenge

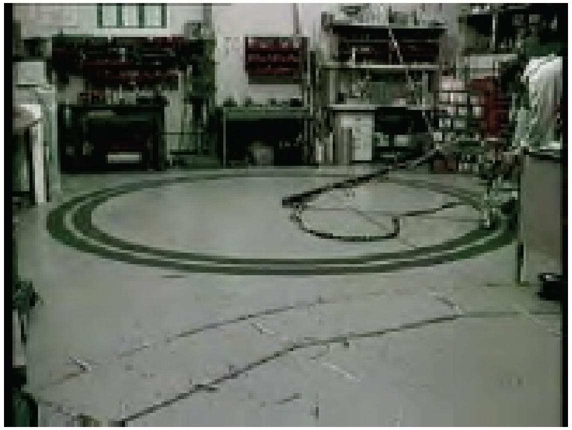
Figure 1: Blue quadrilateral defines the exclusion zone

Biped Robots

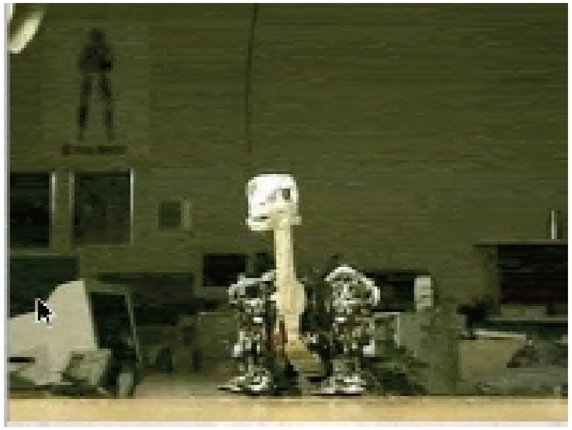
Passive Walking Robot
TU Delft



Turkey (MIT)



Troody (MIT)



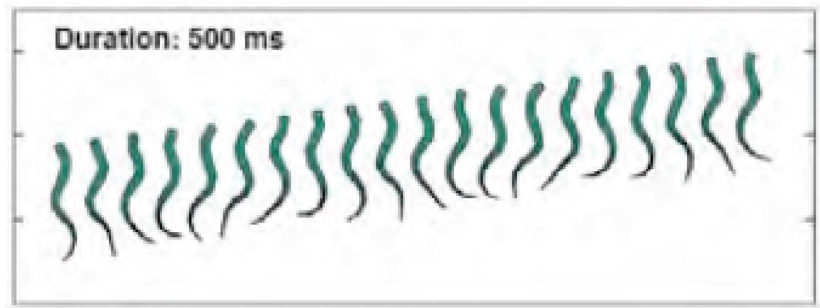
Swimming Gaits

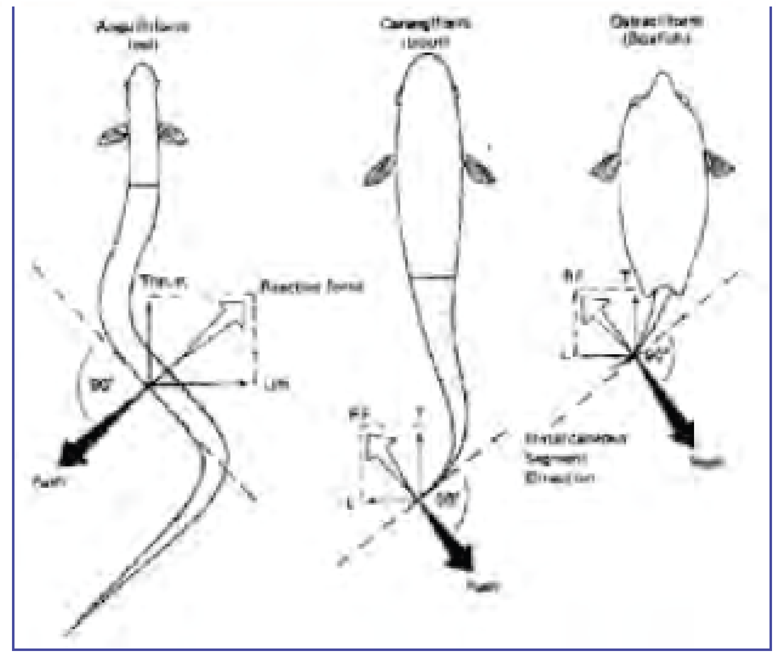
Anguilliform locomotion
Long, slender fish
Little increase in amplitude of flexion wave along the body

Sub-carangiform locomotion
Marked increase in wave amplitude along the body
Majority of work being done by rear half of fish
Stiffer fish body
Higher speed but reduced maneuverability

Carangiform locomotion
Stiffer and faster-moving
Majority of movement rear of body and tail
Rapidly oscillating tails

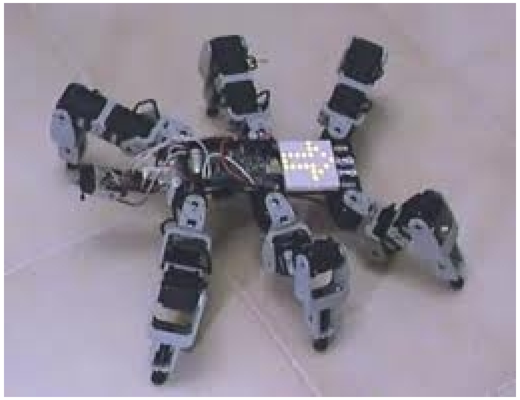
Thunniform locomotion
High-speed long-distance swimmers
Virtually all lateral movement in the tail
Tail itself is large and crescent-shaped





Insect-Like Robots (Hexapod, Spider...)

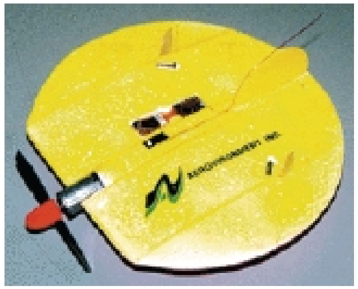
Fraunhofer



Today
Products

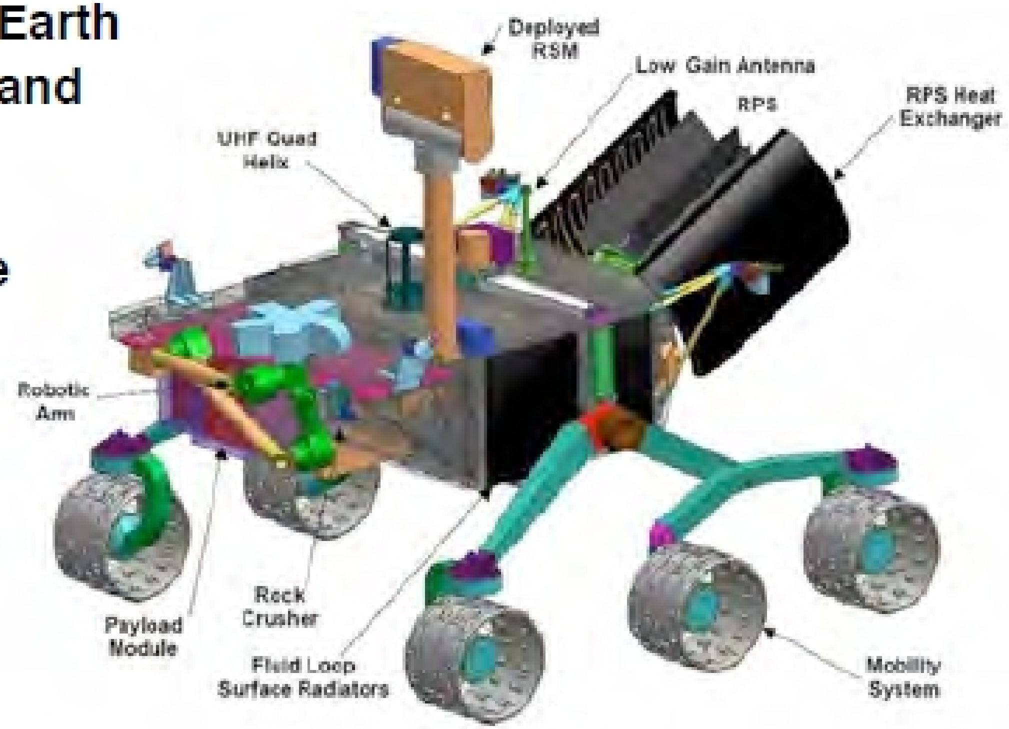
Genghis

Uninhabited Air Vehicles (UAV) and Aircrafts



Mars Science Laboratory

- Transport science payload over Martian surface
  - Rocker-bogie design
- Communications with Earth
- Guidance, navigation, and control
- Power supply
- Support for deployable devices
- Size ~ Mini-Cooper
- In development

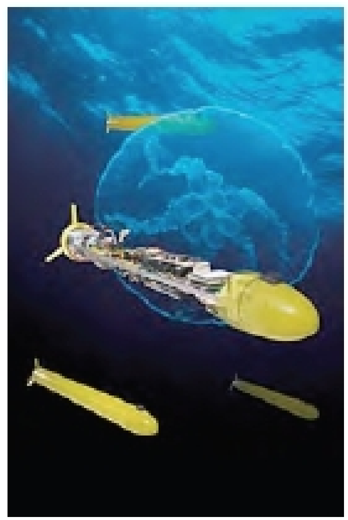


Autonomous Mobile Explorers

- Autonomous Benthic Explorer

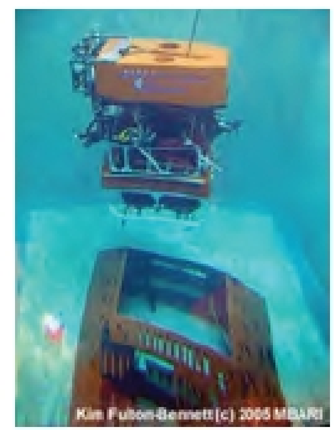
AQUA

- VPI concept



- Oberon (U Sydney)

- MBARI Ventana



UCD DUBLIN

Autonomous Underwater Vehicles

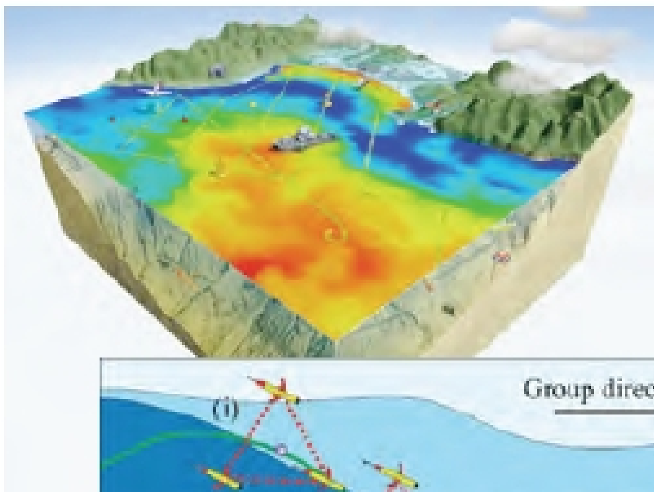
RoboTuna (MIT)

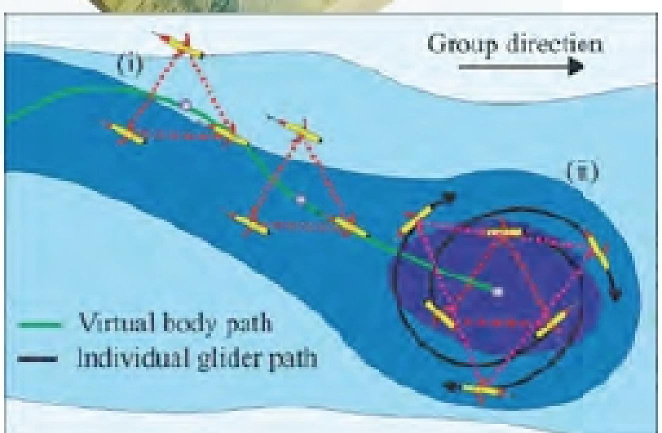
RoboLobster (Northeastern)

http://www.youtube.com/watch?v=FCOZFwzMiU8&NR=1

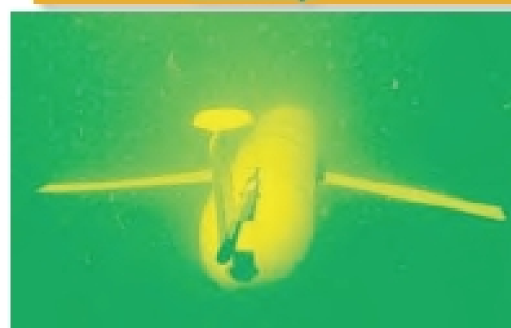
Autonomous Underwater Gliders

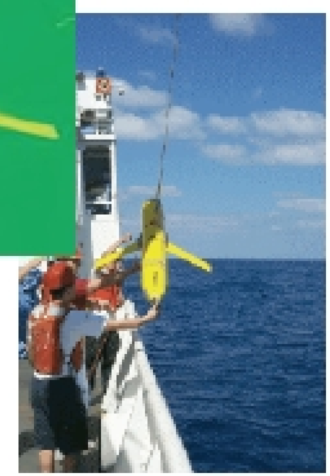
- Monterey Bay Experimental Program





- Slocum Glider
  - Variable ballast for climb and dive
  - Adaptive schooling guidance *(Leonard et al)*





Wheeled and Tracked Robots

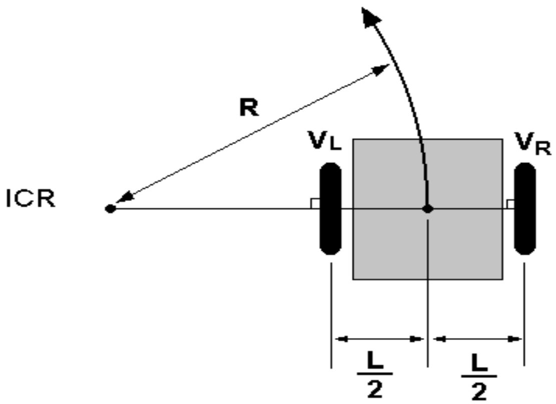
- **Vacuum cleaners (*Roomba*)**
- **Military/Emergency robots (*PackBot*)**
- **DARPA Grand Challenge**

PackBot in Action

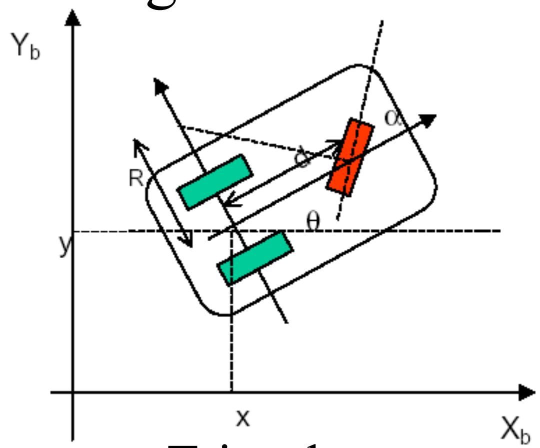
Autonomous Wheelchairs

Mobile Robot Locomotion

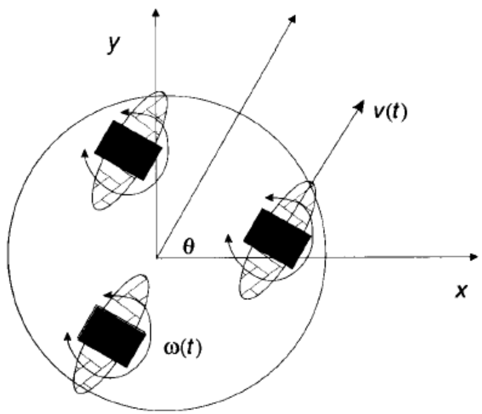
Locomotion: the process of causing a robot to move



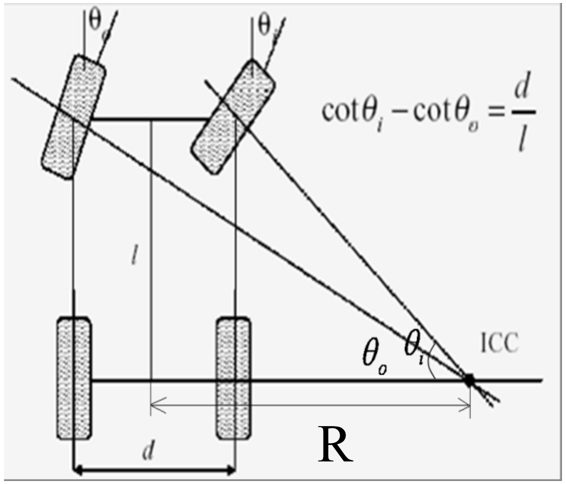
- Differential Drive



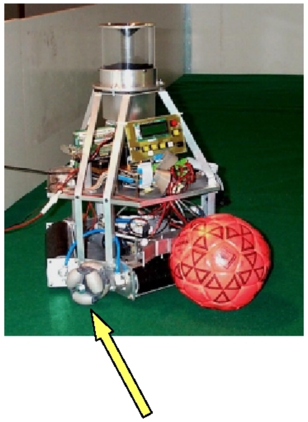
- Tricycle



- Synchronous Drive



- Ackerman Steering

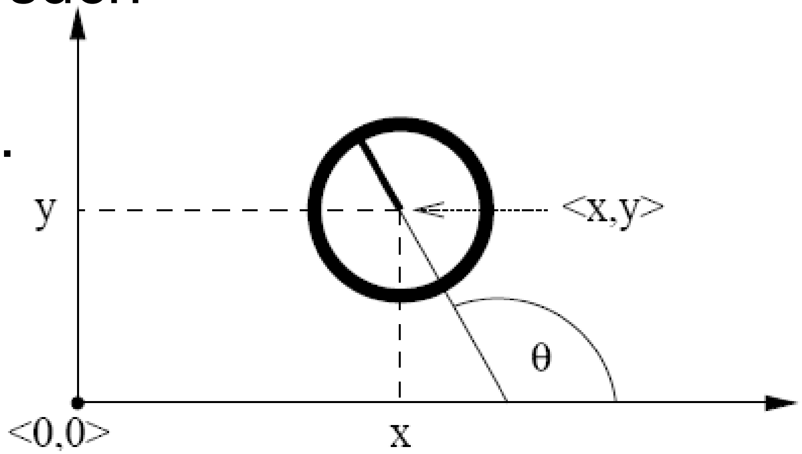


- Omni-directional

Coordinate Systems

- **In general the configuration of a robot can be described by six parameters.**
- **Three-dimensional cartesian coordinates plus three Euler angles yaw, pitch, roll (as in ROS/tf)**
- **Throughout this section, we consider robots operating on a planar surface.**

- The state space of such systems is three-dimensional (x,y,θ).



Mobility, Steerability, and Maneuverability

- Degree of **mobility**, δ_m : **Instantaneous** DOF of robot chassis due to commanding different **wheel velocities** (without turning wheels).

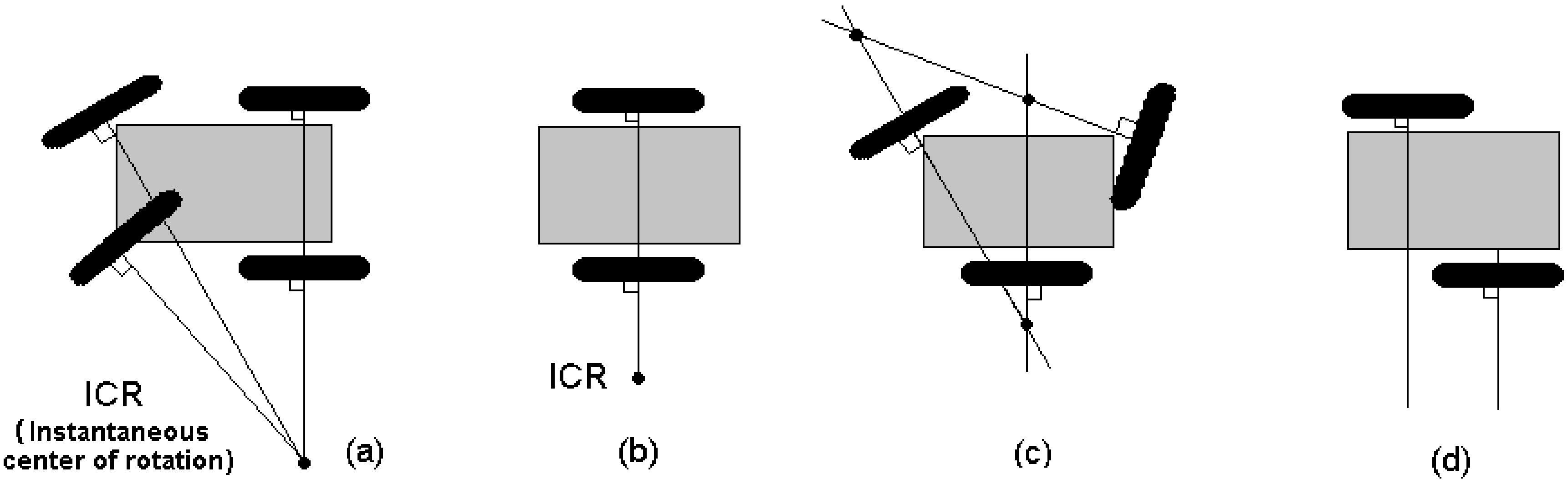
- Degree of **steerability**, δ_s : **Instantaneous** DOF of robot chassis due to **reorienting the wheel**. i.e., the DOF of changing the ICR location on the plane, without actually changing the points of contact of the wheels.

- Degree of **maneuverability**, δ_M : The **long-term** DOF of robot.

$$\delta_M = \delta_m + \delta_s$$

Wheeled mobile robots

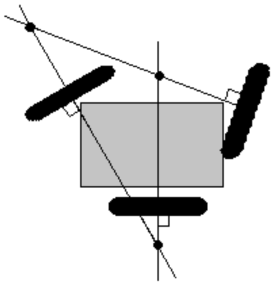
- **Instantaneous center of rotation (ICR)**



Degree of Mobility

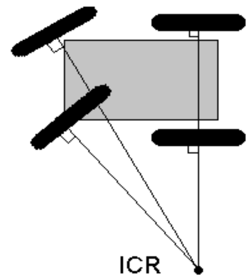
- **Degree of mobility**

The degree of freedom of the robot motion



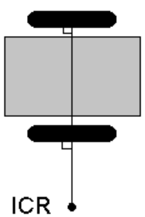
Cannot move anywhere (No ICR)

- Degree of mobility : 0



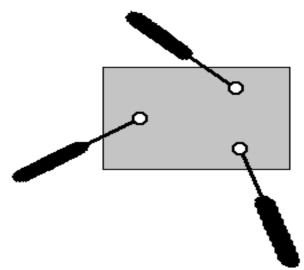
Fixed arc motion (Only one ICR)

- Degree of mobility : 1



Variable arc motion (line of ICRs)

- Degree of mobility : 2



Fully free motion

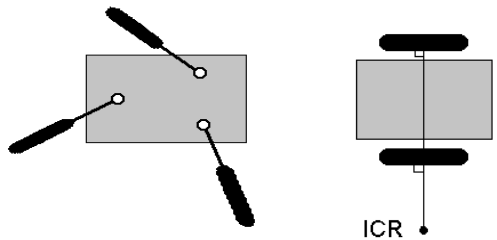
(ICR can be located at any position)

- Degree of mobility : 3

Degree of Steerability

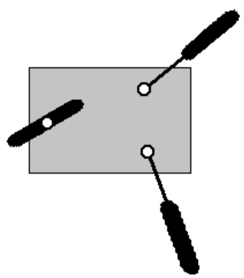
- **Degree of steerability**

  The number of centered orientable wheels that can be steered independently in order to steer the robot

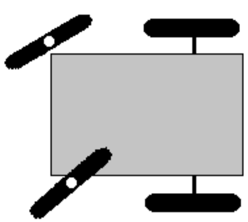


No centered orientable wheels

- Degree of steerability : 0

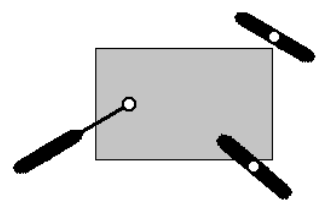


One centered orientable wheel



Two mutually dependent centered orientable wheels

- Degree of steerability : 1

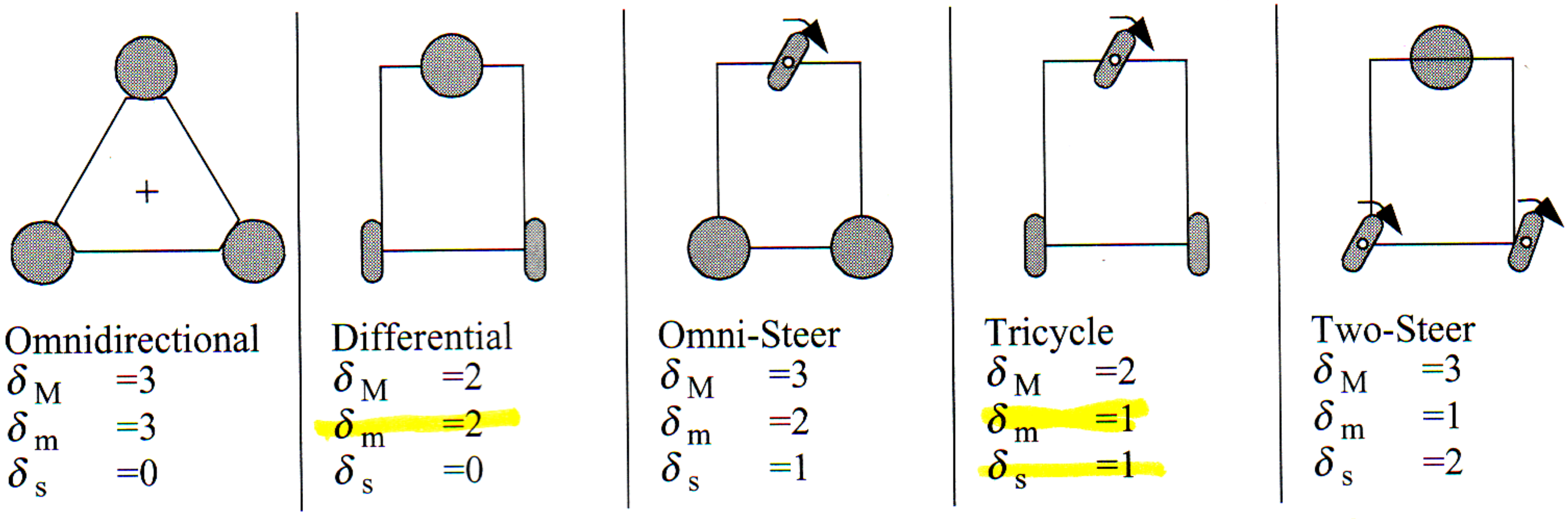


Two mutually independent centered orientable wheels

- Degree of steerability : 2

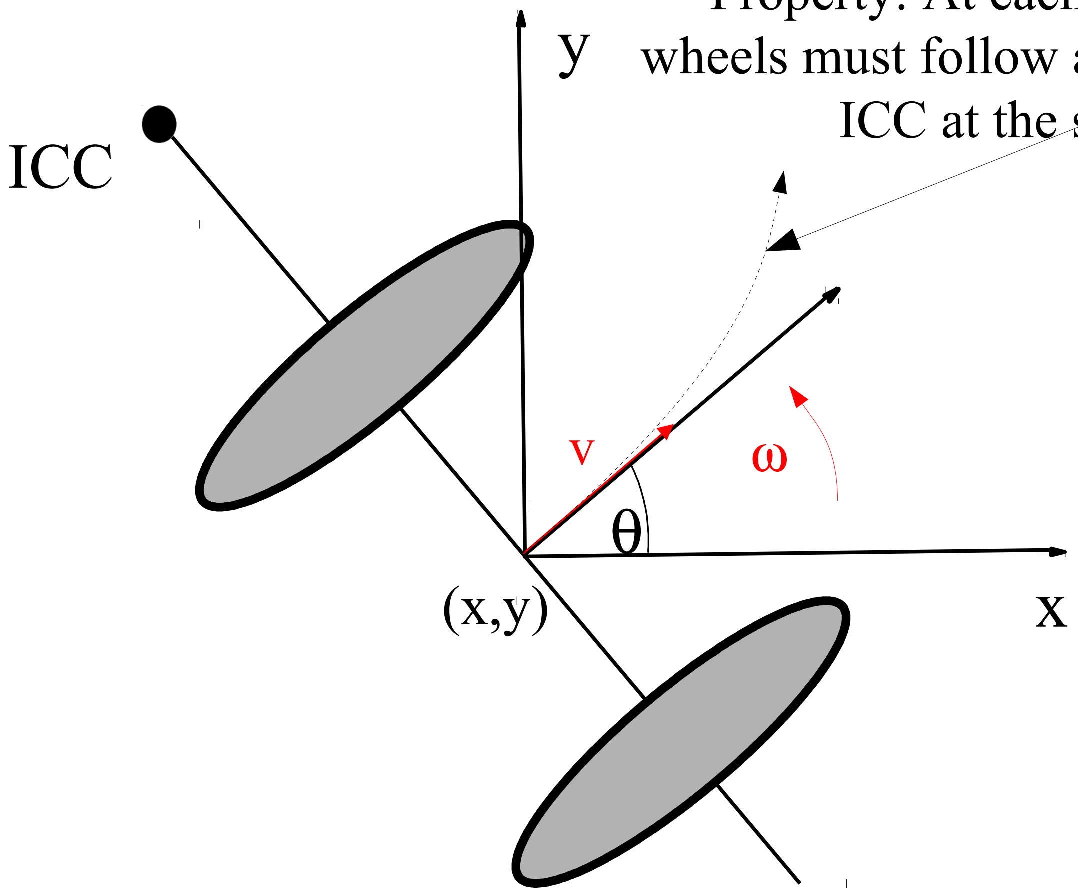
Degree of Maneuverability

$$\delta_M = \delta_m + \delta_s$$



Differential Drive - Kinematic

Property: At each time instant, the left and right wheels must follow a trajectory that moves around the ICC at the same angular rate ω, i.e.,

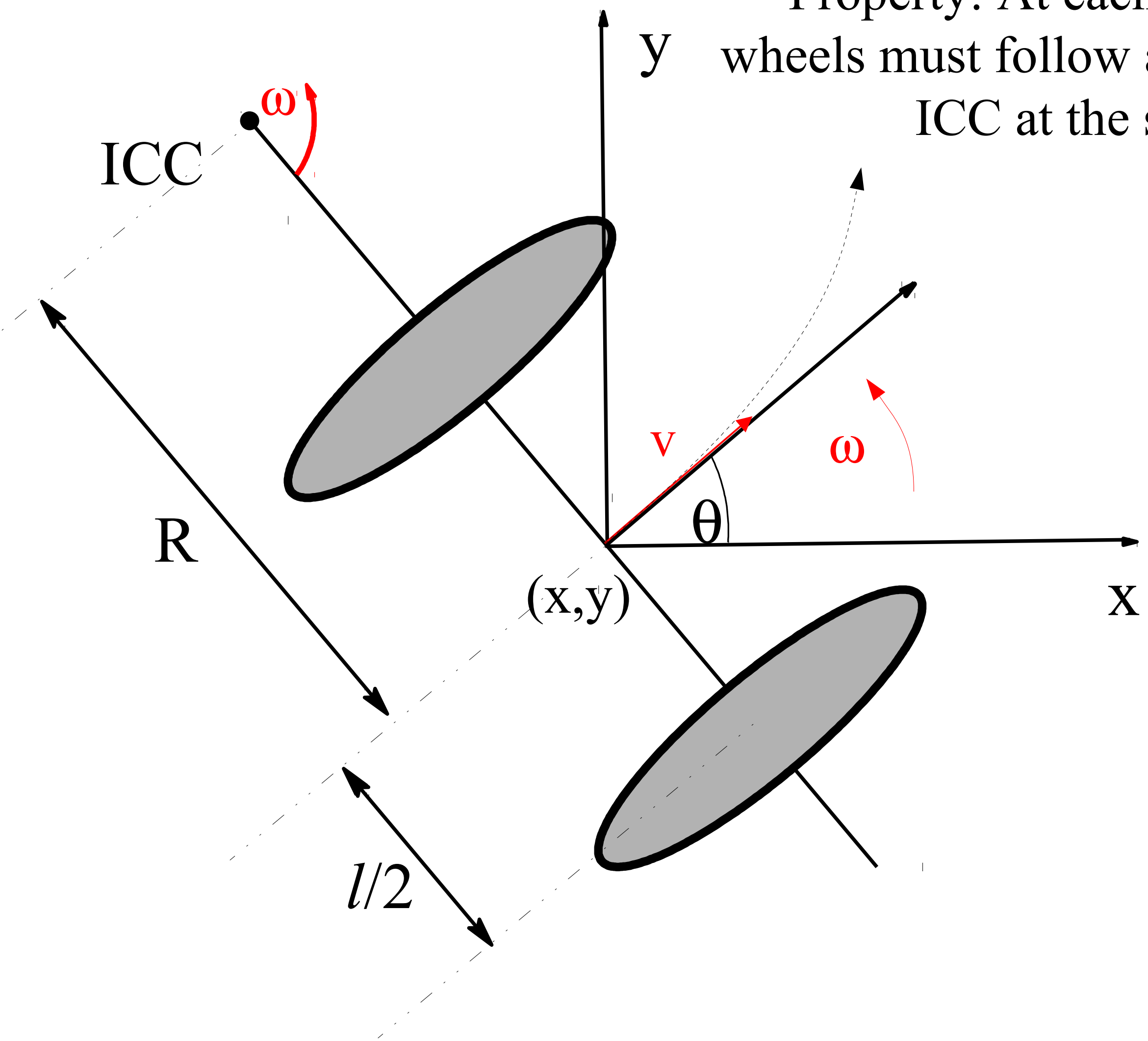


V – Translational Velocity (instantaneous velocity of center point of robot axis)

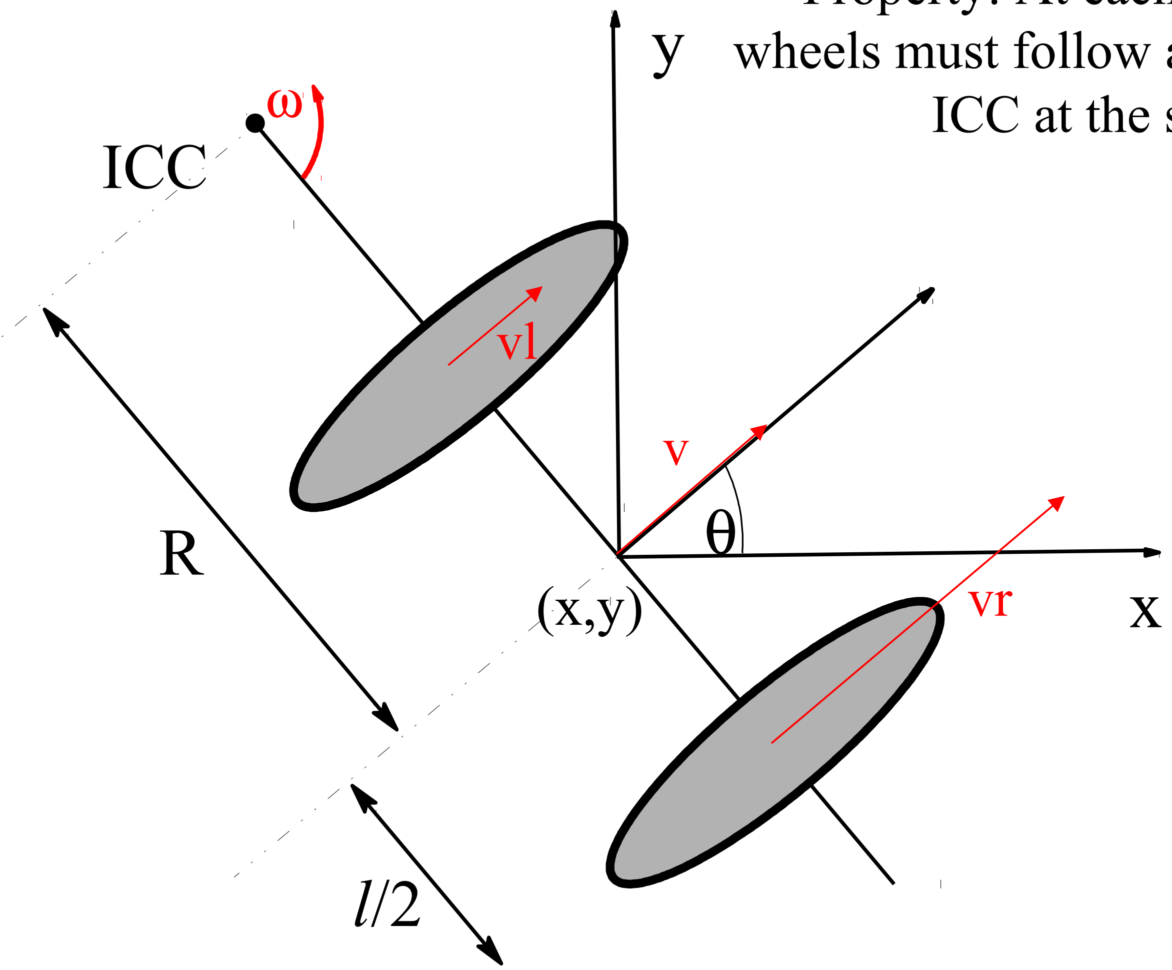
W – Rotational Velocity

Differential Drive - Kinematic

Property: At each time instant, the left and right wheels must follow a trajectory that moves around the ICC at the same angular rate ω, i.e.,



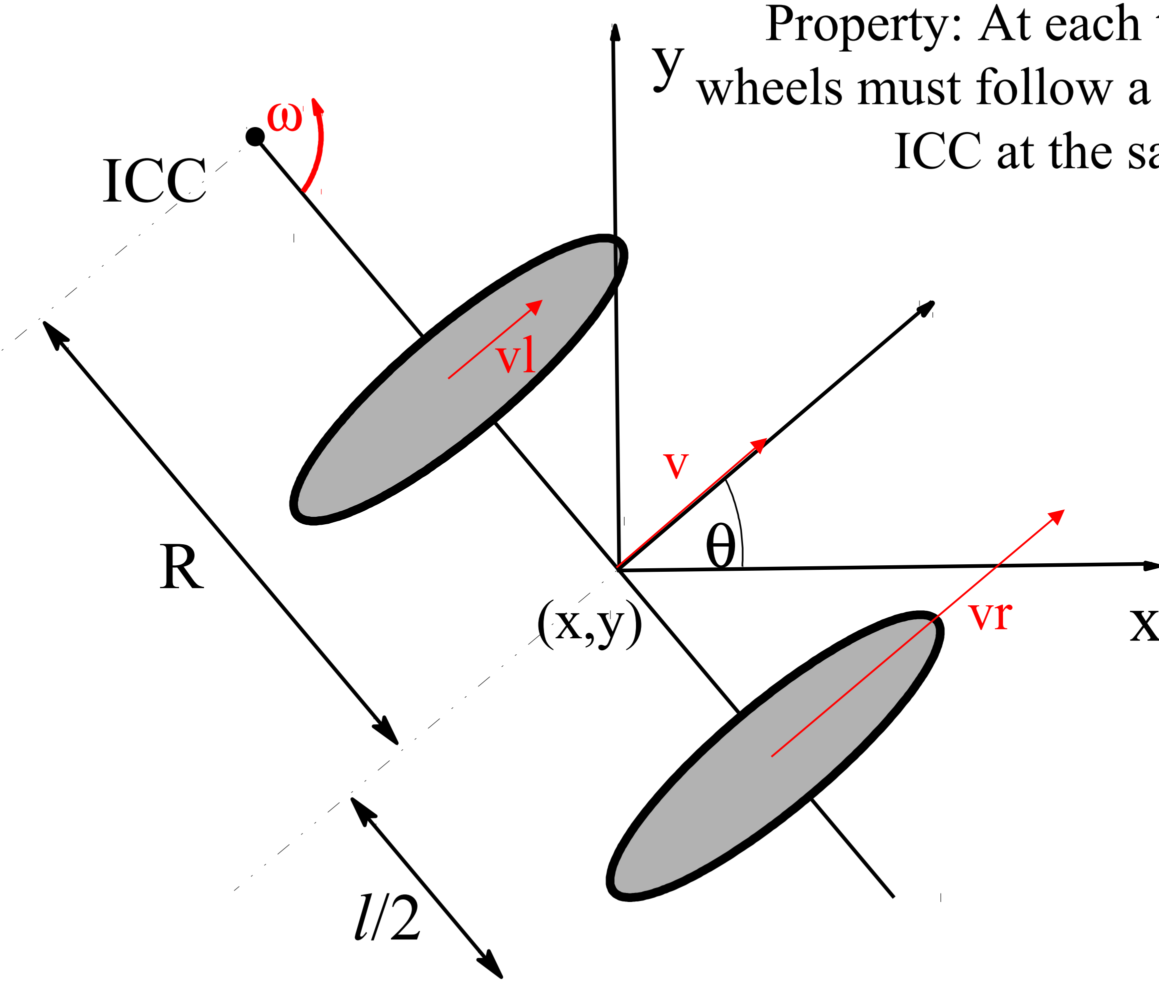
Differential Drive



Property: At each time instant, the left and right wheels must follow a trajectory that moves around the ICC at the same angular rate ω, i.e.,

$$\omega\left(R+l/2\right)=vr$$
$$\omega\left(R-l/2\right)=vl$$

Differential Drive



Property: At each time instant, the left and right wheels must follow a trajectory that moves around the ICC at the same angular rate ω, i.e.,

$$\omega\left(R+l/2\right)=vr$$

$$\omega\left(R-l/2\right)=vl$$

$$R=\frac{l}{2}\frac{\left(vl+vr\right)}{\left(vr-vl\right)}$$

$$\omega=\frac{vr-vl}{l}$$

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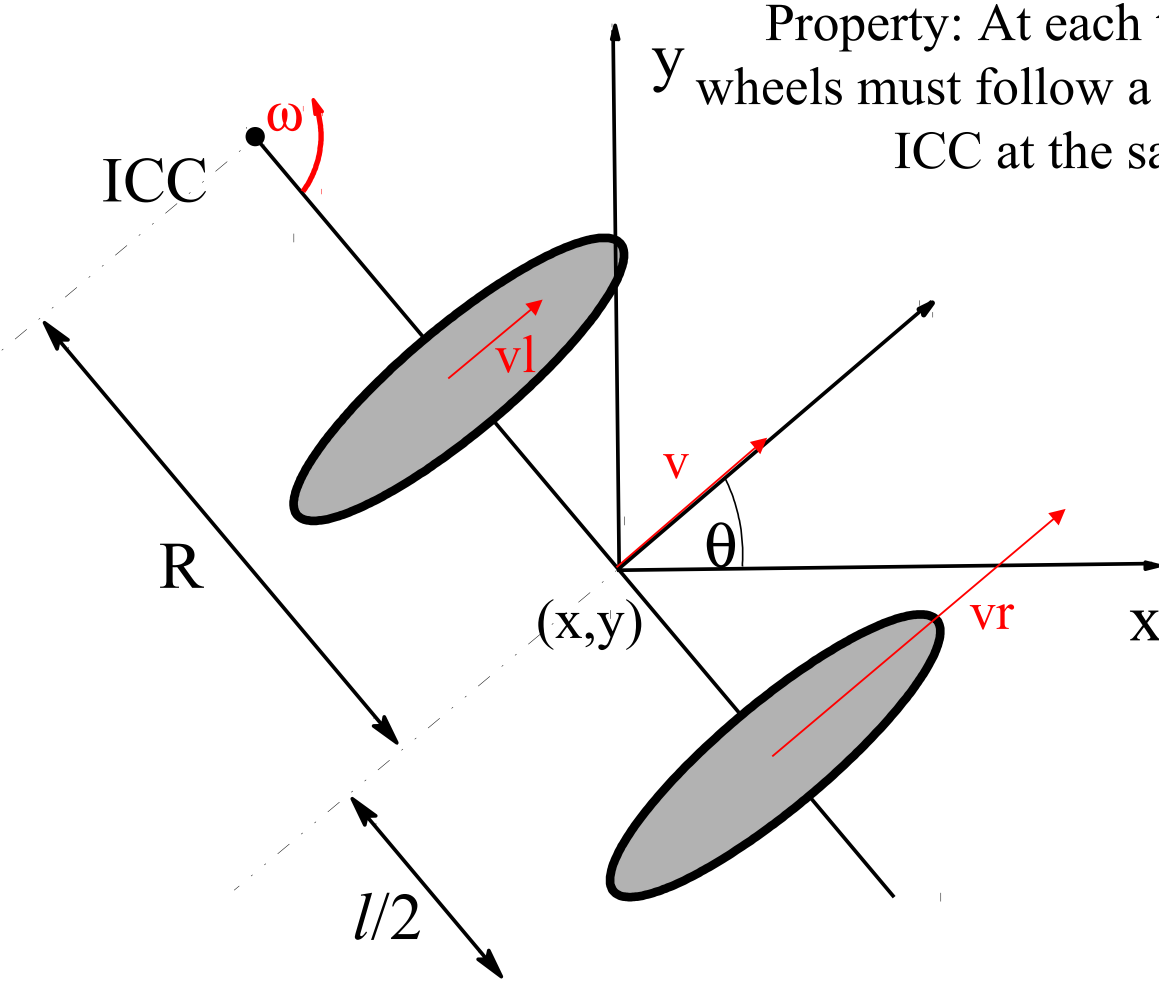

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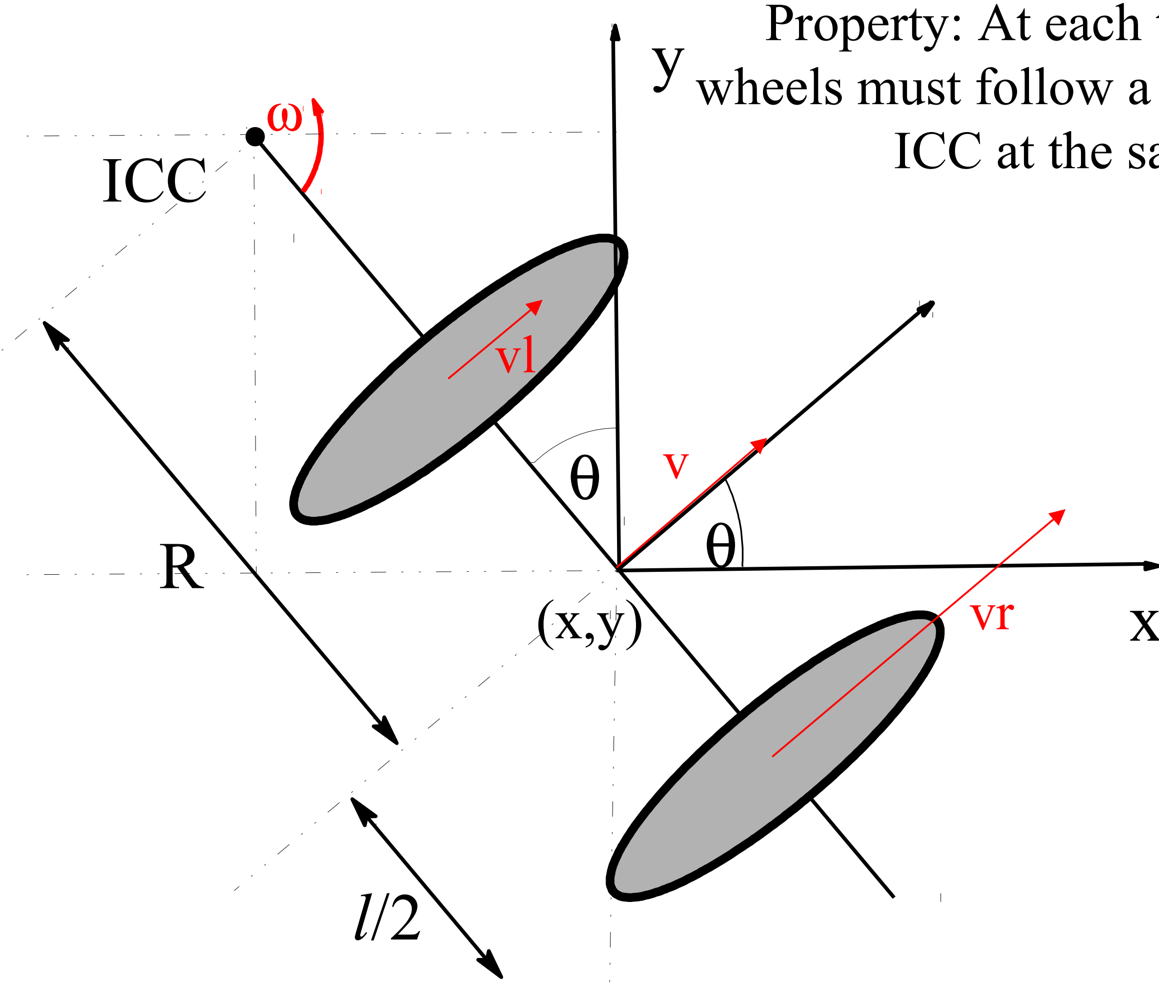

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$$\omega\left(R-l/2\right)=vl$$

$$R=\frac{l}{2}\frac{\left(vl+vr\right)}{\left(vr-vl\right)}$$

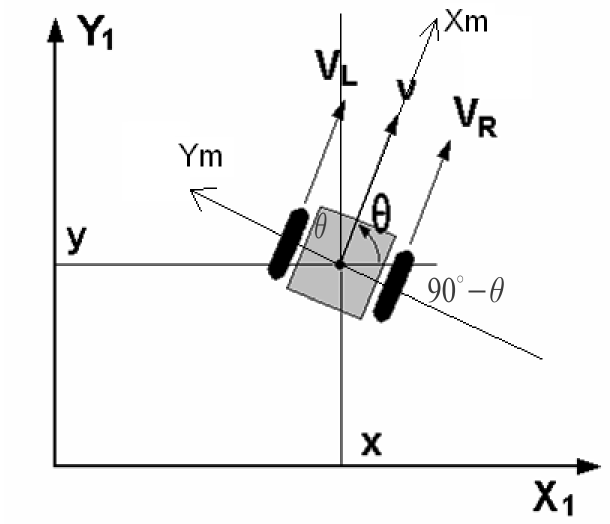
$$\omega=\frac{vr-vl}{l}$$

$$\mathrm{ICC}=\left[x-R\sin\theta, y+R\cos\theta\right]$$

Differential Drive - Kinematic

$$\omega\left(R+\frac{L}{2}\right)=V_R \qquad \omega\left(R-\frac{L}{2}\right)=V_L$$

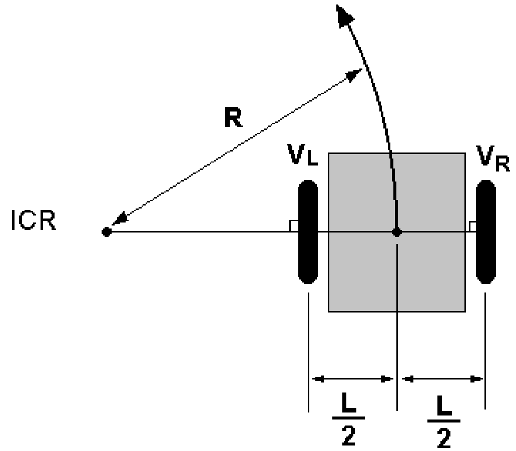
$$\omega=\frac{V_R-V_L}{L} \qquad v=\frac{V_R+V_L}{2}$$



Differential Drive

- **Basic Motion Control**

$$(V_R - V_L)/\ L \ = \ V_R\ /(R + \frac{L}{2})$$



$$R = \frac{L}{2}\,\frac{V_R + V_L}{V_R - V_L}$$

R : Radius of rotation

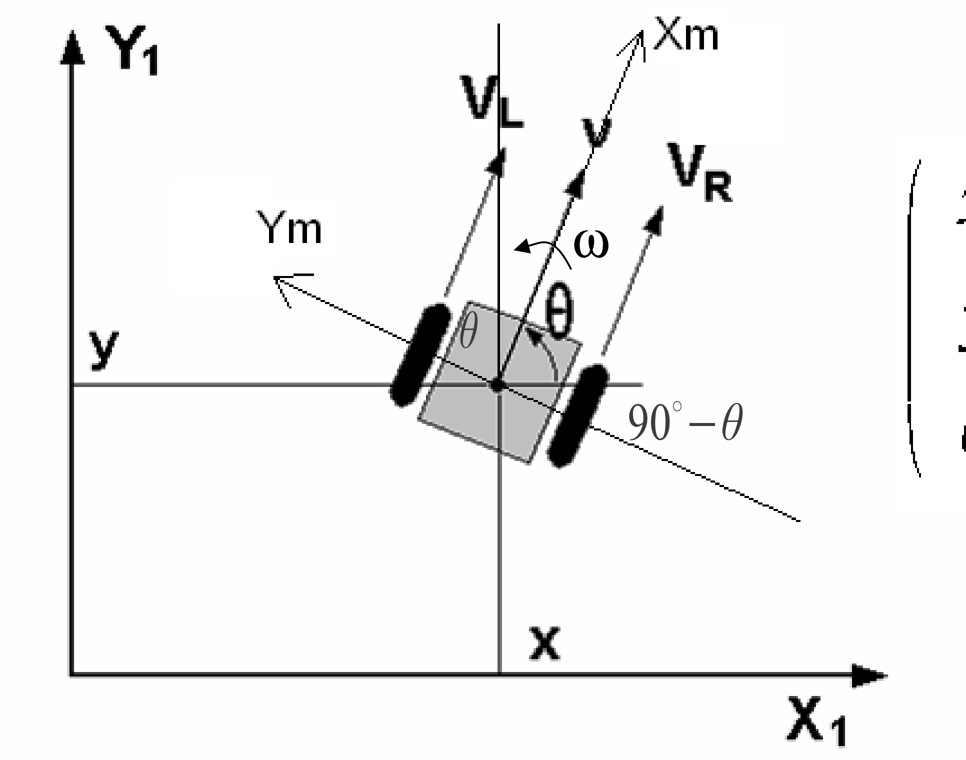
- Straight motion

R = Infinity $\rightarrow$ $V_R = V_L$

- Rotational motion

R = 0 $\rightarrow$ $V_R = -V_L$

Differential Drive - Kinematic



$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} v \\ \omega \end{pmatrix}$$

This Friday: Dead Reckoning & Localization

- **Derived from "deduced reckoning."**
- **Mathematical procedure for determining the present location of a vehicle.**
- **Achieved by calculating the current pose of the vehicle based on its velocities and the time elapsed.**

Tricycle

- Steering and power are provided through the front wheel
  - control variables:
    - angular velocity of steering wheel $w_s(t)$
    - steering direction $\alpha(t)$

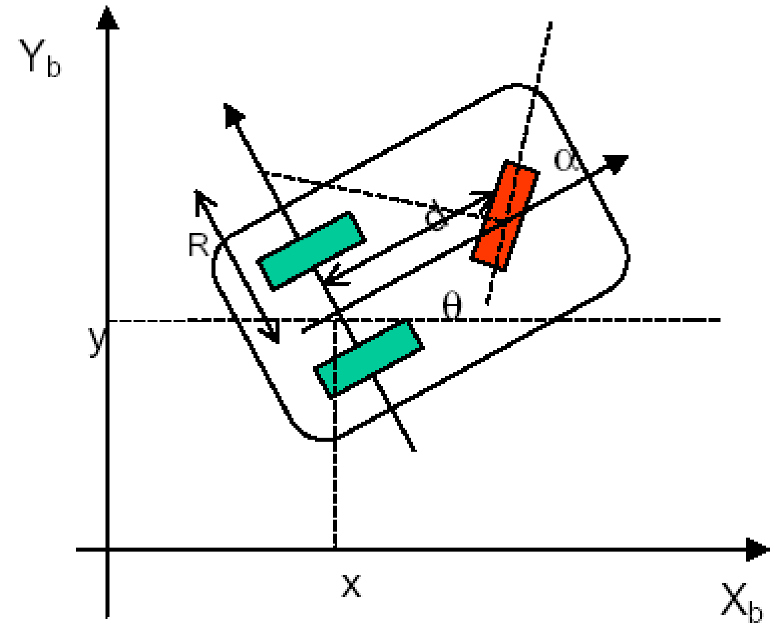
r = steering wheel radius

$$v_s(t) = w_s(t)\, r$$ linear velocity of steering wheel

$$R(t) = d\, \mathrm{tg}\left(\pi/2 - \alpha(t)\right)$$

$$w(t) = \frac{w_s(t)\, r}{\sqrt{d^2 + R(t)^2}}$$ angular velocity of the moving fram relative to the base frame

$$w(t) = \frac{v_s(t)}{d} \sin\alpha(t)$$



d: distance from the front wheel to the rear axle

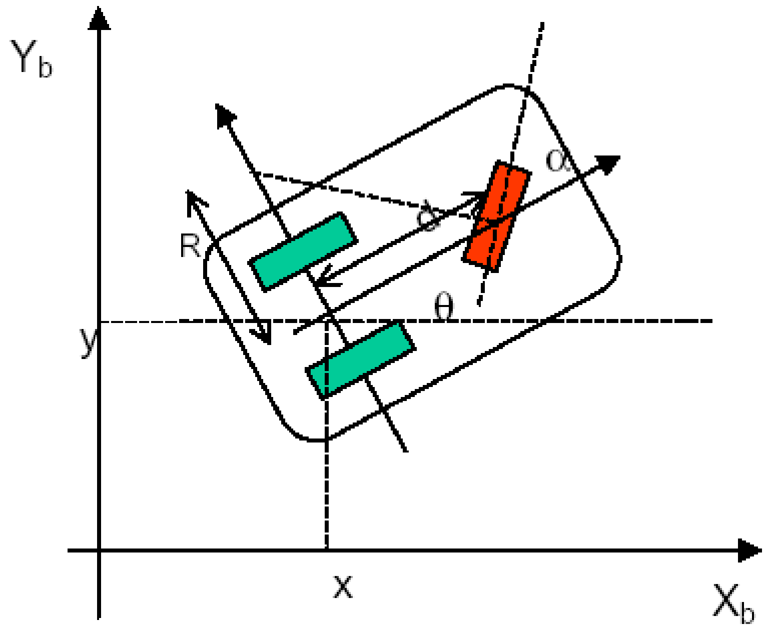
Tricycle

Kinematics model in the world frame ---Posture kinematics model

$$\dot{x}(t) = v_s(t)\cos\alpha(t)\cos\theta(t)$$
$$\dot{y}(t) = v_s(t)\cos\alpha(t)\sin\theta(t)$$
$$\dot{\theta}(t) = \frac{v_s(t)}{d}\sin\alpha(t)$$

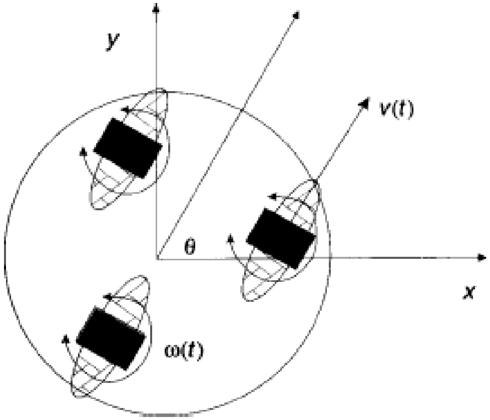
$$\begin{bmatrix}\dot{x}(t)\\ \dot{y}(t)\\ \dot{\theta}(t)\end{bmatrix} = \begin{bmatrix}\cos\theta(t) & 0\\ \sin\theta(t) & 0\\ 0 & 1\end{bmatrix}\begin{bmatrix}v(t)\\ w(t)\end{bmatrix}$$

$$v(t) = v_s(t)\cos\alpha(t)$$
$$w(t) = \frac{v_s(t)}{d}\sin\alpha(t)$$



Synchronous Drive

- **All the wheels turn in unison**
  - All wheels point in the same direction and turn at the same rate
  - Two independent motors, one rolls all wheels forward, one rotate them for turning
- **Control variables (independent)**
  - v(t), ω(t)



$$x(t) = \int_0^t v(\sigma)\cos(\theta(\sigma))d\sigma$$

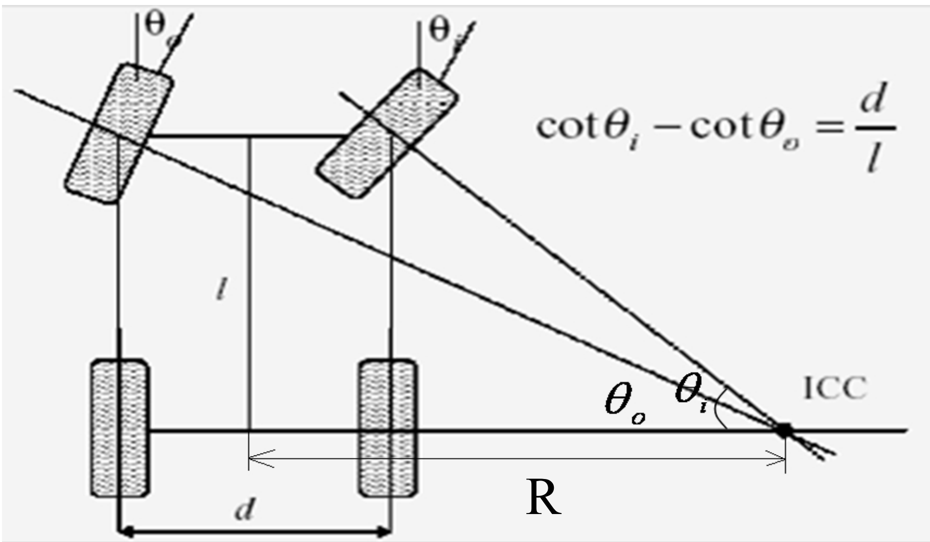
$$y(t) = \int_0^t v(\sigma)\sin(\theta(\sigma))d\sigma$$

$$\theta(t) = \int_0^t w(\sigma)d\sigma$$

Ackerman Steering (Car Drive)

- **The Ackerman Steering equation:**
  - : $$\cot\theta_i - \cot\theta_o = \frac{d}{l}$$

$$\cot\theta = \frac{\cos\theta}{\sin\theta}$$



$$\cot\theta_i - \cot\theta_o$$

$$\frac{R+d/2}{l} - \frac{R-d/2}{l}$$

$$\frac{d}{l}$$

Robot Sensing and Sensors

What is Sensing ?

- Collect information about the world
- Sensor - an electrical/mechanical/chemical device that maps an environmental attribute to a quantitative measurement
- Each sensor is based on a *transduction principle -* conversion of energy from one form to another

Human sensing and organs

- Vision: eyes (optics, light)
- Hearing: ears (acoustics, sound)
- Touch: skin (mechanics, heat)
- Odor: nose (vapor-phase chemistry)
- Taste: tongue (liquid-phase chemistry)

Extended ranges and modalities

- **Vision outside the RGB spectrum**
  - Infrared Camera, see at night
- **Active vision**
  - Radar and optical (laser) range measurement
- **Hearing outside the 20 Hz – 20 kHz range**
  - Ultrasonic range measurement
- **Chemical analysis beyond taste and smell**
- **Radiation: α, β, γ-rays, neutrons, etc**

Transduction to electronics

- Thermistor: temperature-to-resistance
- Electrochemical: chemistry-to-voltage
- Photocurrent: light intensity-to-current
- Pyroelectric/Piezoelectric: thermal radiation-to-voltage
- Humidity: humidity-to-capacitance
- Length (LVDT: Linear variable differential transformers) : position-to-inductance
- Microphone: sound pressure-to-<anything>

Classification of Sensors

- **Proprioception (Internal state) v.s. Exteroceptive (external state)**
  - *measure values internally to the system (robot),* e.g. battery level, wheel position, joint angle, etc,
  - observation of environments, objects
- **Active v.s. Passive**
  - emitting energy into the environment, e.g., radar, sonar
  - passively receive energy to make observation, e.g., camera

Contact v.s. non-contact

Bumper, vs laser/sonars

Proprioceptive Sensors

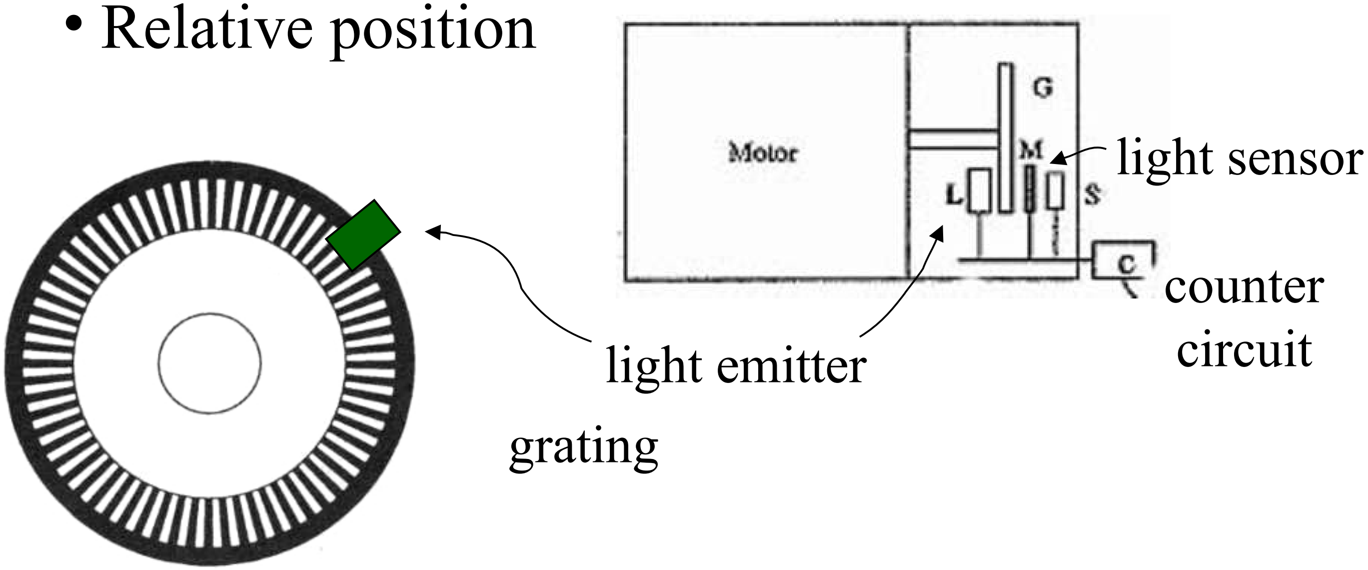
- **Encoders, Potentiometers**
  - measure angle of turn via change in resistance or by counting optical pulses
- **Gyroscopes**
  - measure rate of change of angles
  - fiber-optic (newer, better), magnetic (older)
- **Compass**
  - measure which way is north
- **GPS: measure location relative to globe**

Sensors Used in Robot

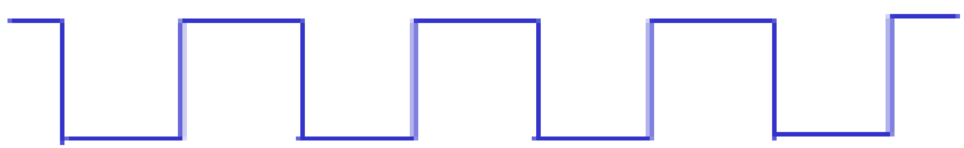
- **Resistive sensors**
  - bend sensors, potentiometer, resistive photocells, ...
- **Tactile sensors**
  - contact switch, bumpers…
- **Infrared sensors**
  - Reflective, proximity, distance sensors…
- **Ultrasonic Distance Sensor**
- **Inertial Sensors (measure the second derivatives of position)**
  - Accelerometer, Gyroscopes,
- **Orientation Sensors**
  - Compass, Inclinometer
- **Laser range sensors**
- **Vision, GPS, …**

Incremental Optical Encoders

• Relative position

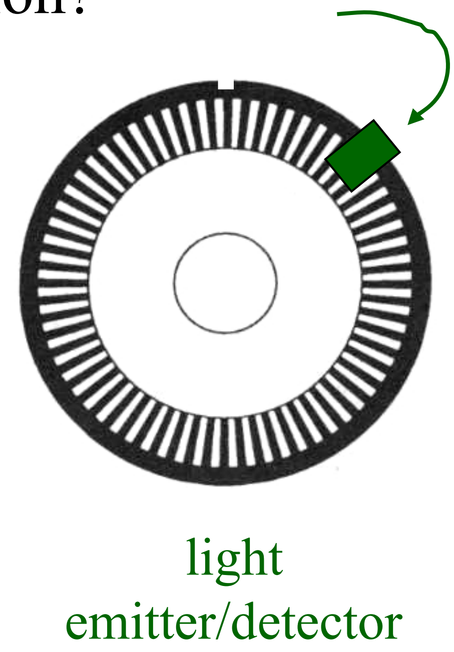


- calibration ?
- direction ?
- resolution ?



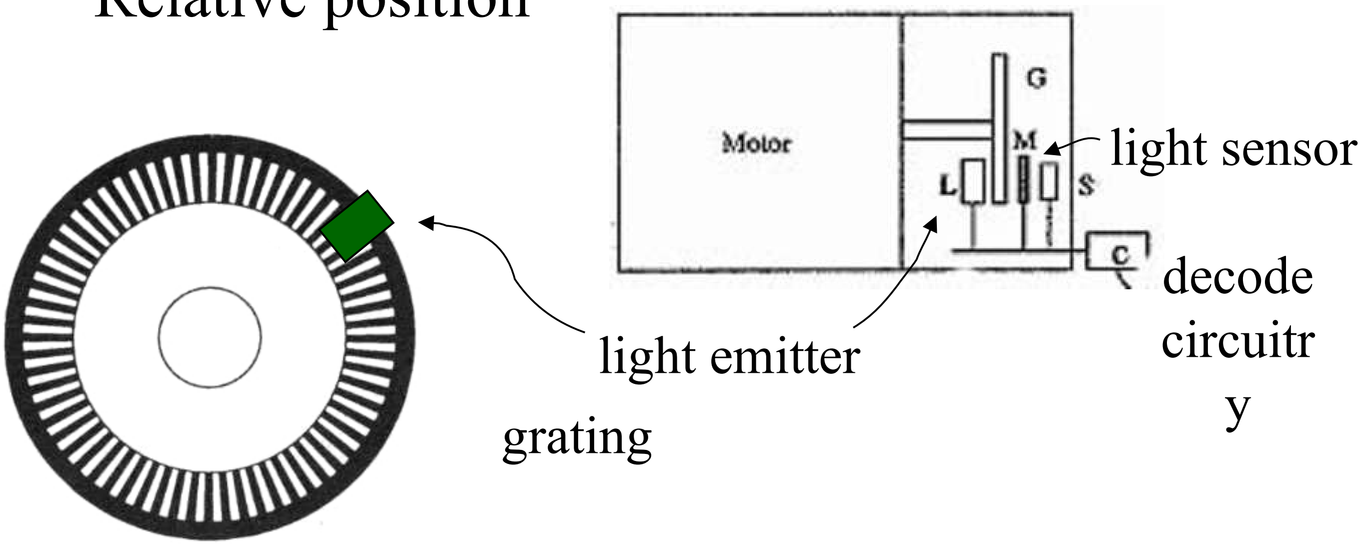
Incremental Optical Encoders

How could you augment a grating-based (relative) encoder in order to detect the *direction* of rotation?

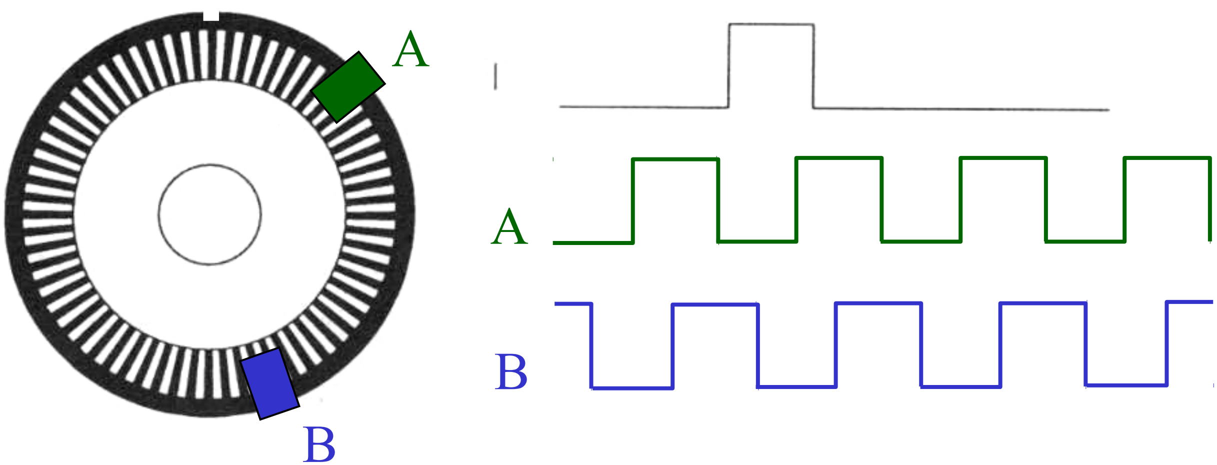


Incremental Optical Encoders

- Relative position



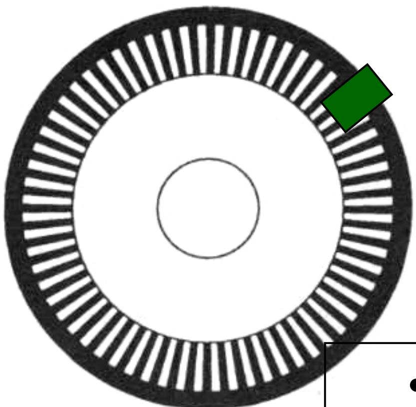
- calibration ?
- direction ?
- resolution ?

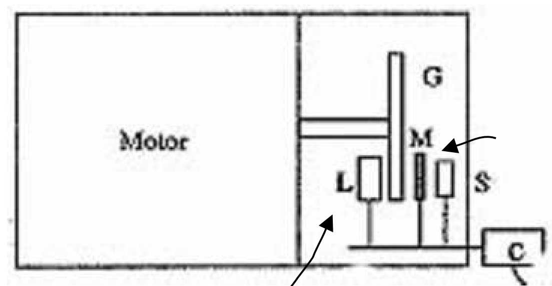


A leads B

Incremental Optical Encoders

- Incremental Encoder:





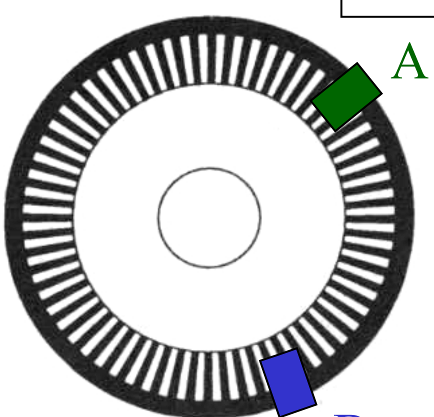
light emitter

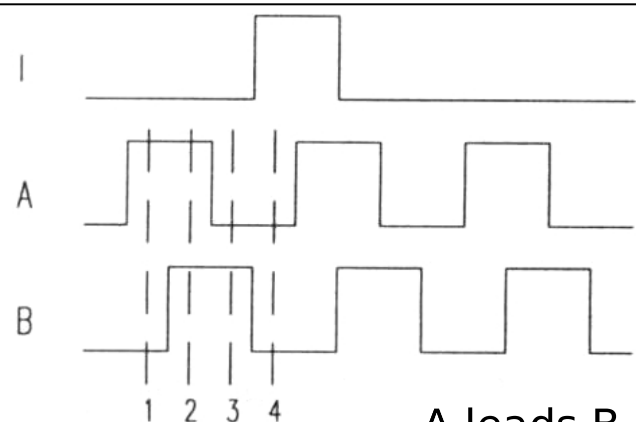
light sensor

decode circuitry

- direction
- resolution

- It generates pulses proportional to the rotation speed of the shaft.
- **Direction** can also be indicated with a two phase encoder:



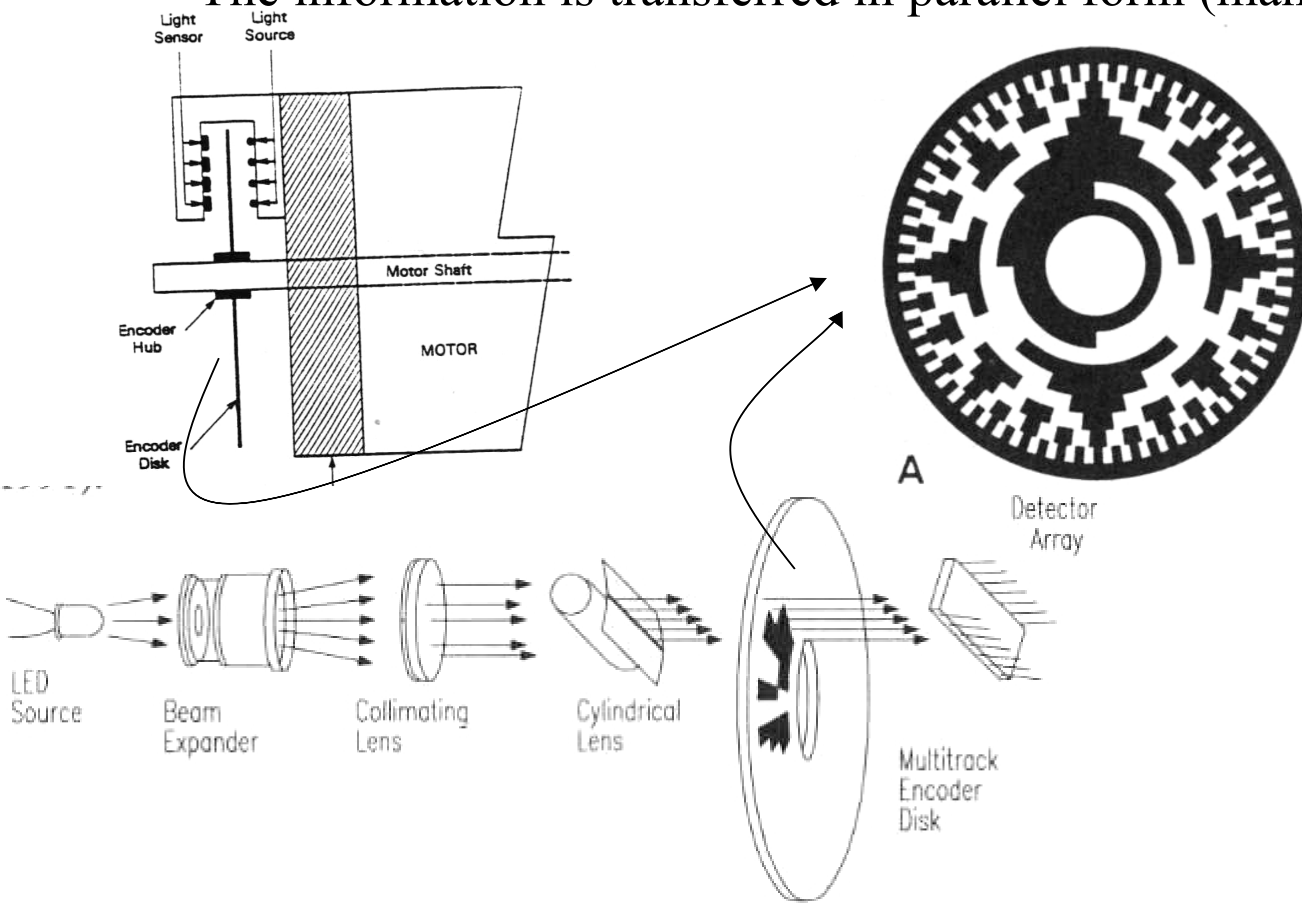


A leads B

State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

Absolute Optical Encoders

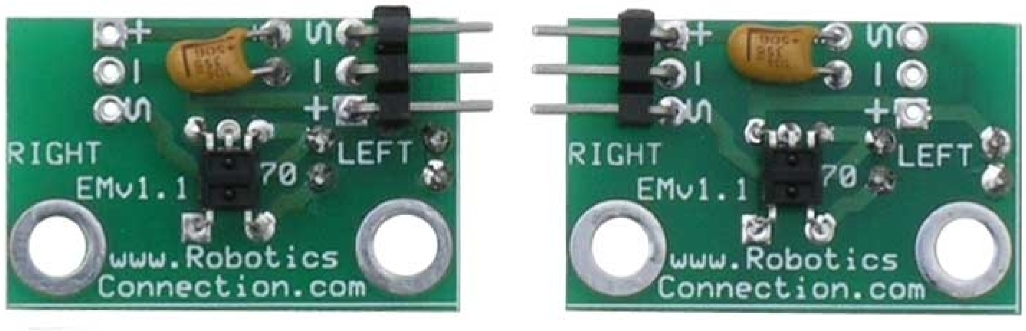
- Used when loss of reference is not possible.
- Gray codes: only one bit changes at a time (less uncertainty).
- The information is transferred in parallel form (many wires are necessary).



Binary	Gray Code
000	000
001	001
010	011
011	010
100	110
101	111
110	101
111	100

Example Wheel Encoders

These modules require +5V and GND to power them, and provide a 0 to 5V output. They provide +5V output when they "see" white, and a 0V output when they "see" black.



These disks are manufactured out of high quality laminated color plastic to offer a very crisp black to white transition. This enables a wheel encoder sensor to easily see the transitions.

Source: http://www.active-robots.com/

Dead Reckoning

- **Derived from "deduced reckoning."**

- **Mathematical procedure for determining the present location of a vehicle.**

- **Achieved by calculating the current pose of the vehicle based on its velocities and the time elapsed.**

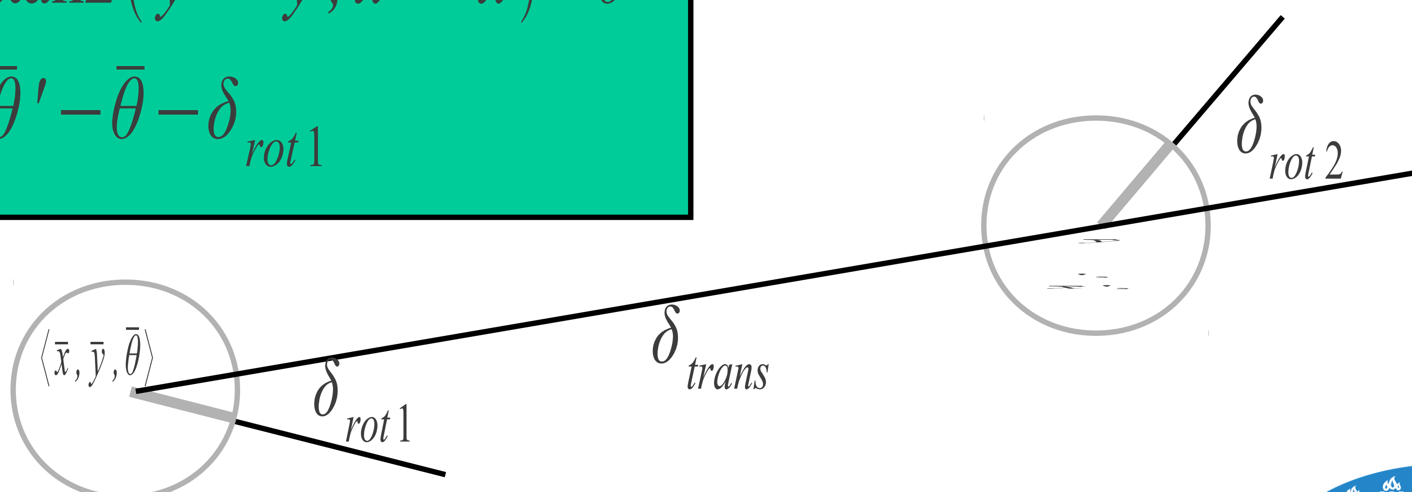
Odometry Model

- Robot moves from $\langle \bar{x}, \bar{y}, \bar{\theta} \rangle$ to .
- Odometry information $u = \langle \delta_{rot1}, \delta_{rot2}, \delta_{trans} \rangle$

$$\delta_{trans} = \sqrt{(\bar{x}' - \bar{x})^2 + (\bar{y}' - \bar{y})^2}$$

$$\delta_{rot1} = \operatorname{atan2}(\bar{y}' - \bar{y}, \bar{x}' - \bar{x}) - \bar{\theta}$$

$$\delta_{rot2} = \bar{\theta}' - \bar{\theta} - \delta_{rot1}$$



The atan2 Function

- Extends the inverse tangent and correctly copes with the signs of x and y.

$$\mathrm{atan2}(y,x) \;=\; \begin{cases} \mathrm{atan}(y/x) & \text{if } x>0 \\ \mathrm{sign}(y)\,(\pi-\mathrm{atan}(|y/x|)) & \text{if } x<0 \\ 0 & \text{if } x=y=0 \\ \mathrm{sign}(y)\,\pi/2 & \text{if } x=0, y\neq 0 \end{cases}$$

Noise Model for Odometry

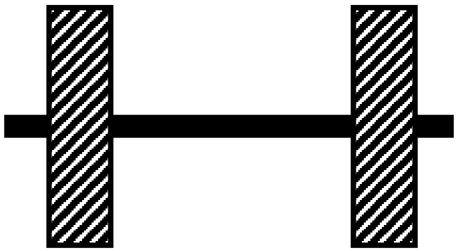
- **The measured motion is given by the true motion corrupted with noise.**

$$\hat{\delta}_{rot1} = \delta_{rot1} + \varepsilon_{\alpha_1 |\delta_{rot1}| + \alpha_2 |\delta_{trans}|}$$

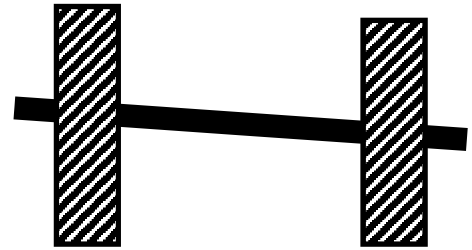
$$\hat{\delta}_{trans} = \delta_{trans} + \varepsilon_{\alpha_3 |\delta_{trans}| + \alpha_4 |\delta_{rot1} + \delta_{rot2}|}$$

$$\hat{\delta}_{rot2} = \delta_{rot2} + \varepsilon_{\alpha_1 |\delta_{rot2}| + \alpha_2 |\delta_{trans}|}$$

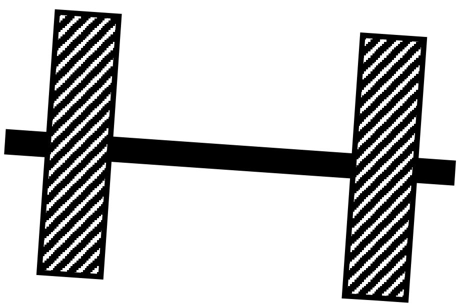
Reasons for Motion Errors



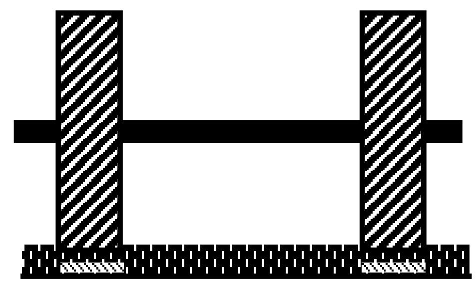
ideal case



different wheel diameters



bump



carpet

and many more …

Inertial Sensors

- **Gyroscopes**
  - Measure the rate of rotation independent of the coordinate frame
  - Common applications:
    - Heading sensors, Full Inertial Navigation systems (INS)
- **Accelerometers**
  - Measure accelerations with respect to an inertial frame
  - Common applications:
    - Tilt sensor in static applications, Vibration Analysis, Full INS Systems

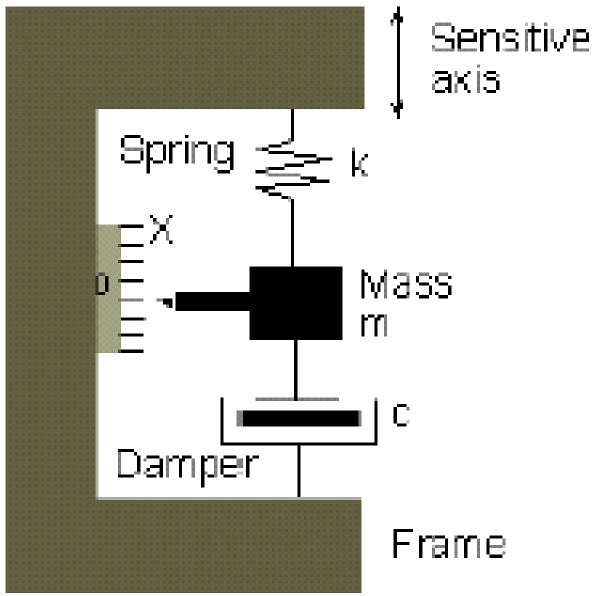
Accelerometers

- **They measure the inertia force generated when a mass is affected by a change in velocity.**
- **This force may change**
  - The tension of a string
  - The deflection of a beam
  - The vibrating frequency of a mass

Accelerometer

- **Main elements of an accelerometer:**

1. Mass 2. Suspension mechanism3. Sensing element

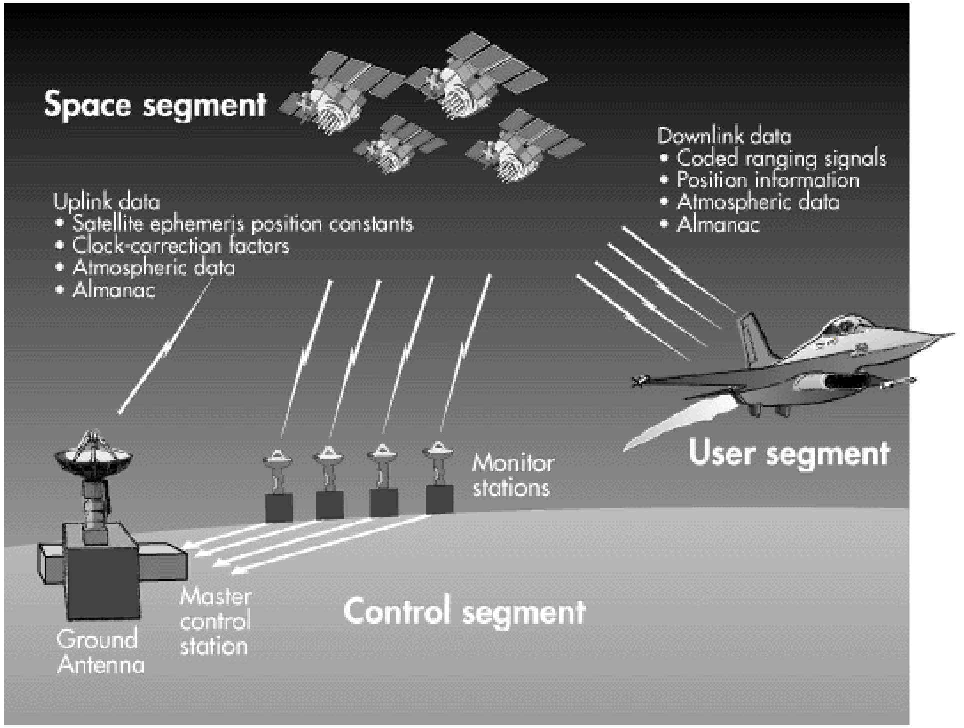


$$F = m\frac{d^2x}{d^2t} + c\frac{dx}{dt} + kx$$

Global Positioning System (GPS)

24 satellites (+several spares)

broadcast time, identity, orbital parameters (latitude, longitude, altitude)



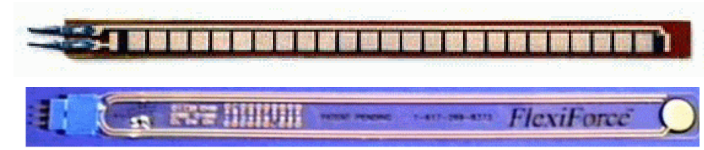
Space Segment

http://www.cnde.iastate.edu/staff/swormley/gps/gp

Resistive Sensors

Bend Sensors

- Resistance = 10k to 35k
- As the strip is bent, resistance increases



Resistive Bend Sensor

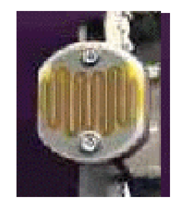
Potentiometers

- Can be used as position sensors for sliding mechanisms or rotating shafts
- Easy to find, easy to mount

Potentiometer

Light Sensor (Photocell)

- Good for detecting direction/presence of light
- Non-linear resistance
- Slow response to light changes

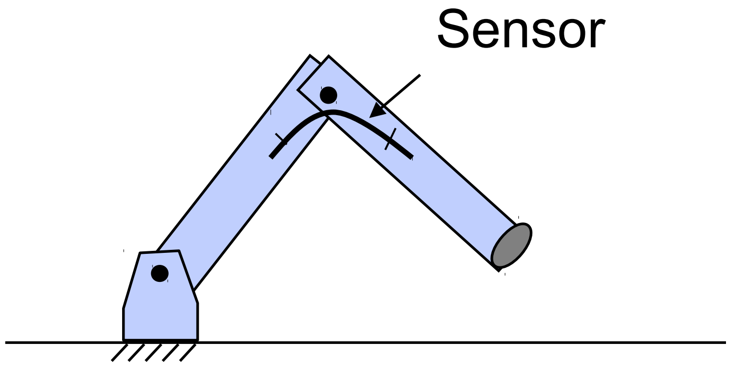


Photocell

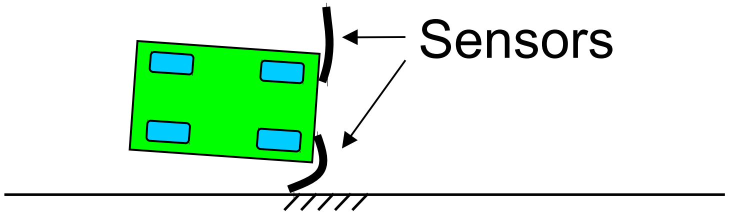
R is small when brightly illuminated

Applications

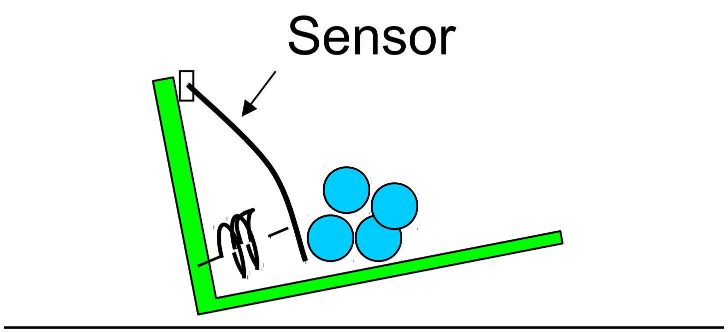
- Measure bend of a joint



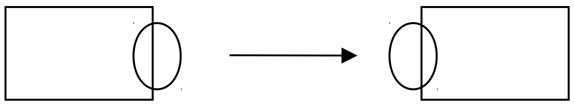
- Wall Following/Collision Detection

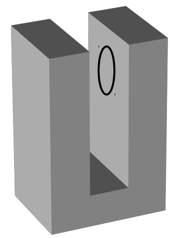


- Weight Sensor

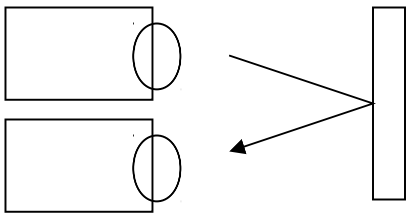


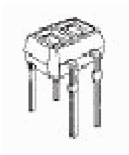
Intensity Based Infrared



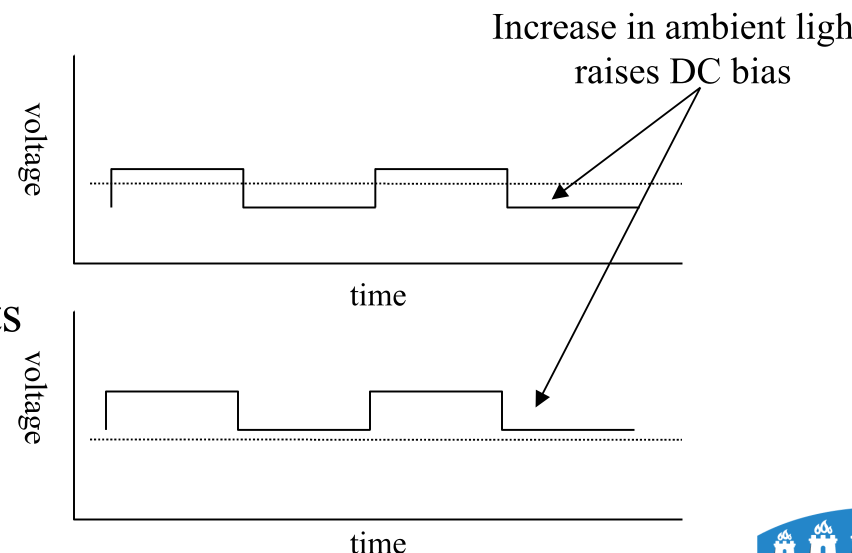


Break-Beam sensor





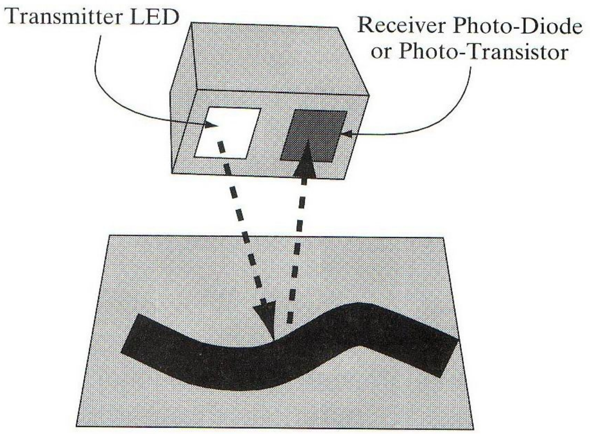
Reflective Sensor



- Easy to implement (few components)
- Works very well in controlled environments
- Sensitive to ambient light

IR Reflective Sensors

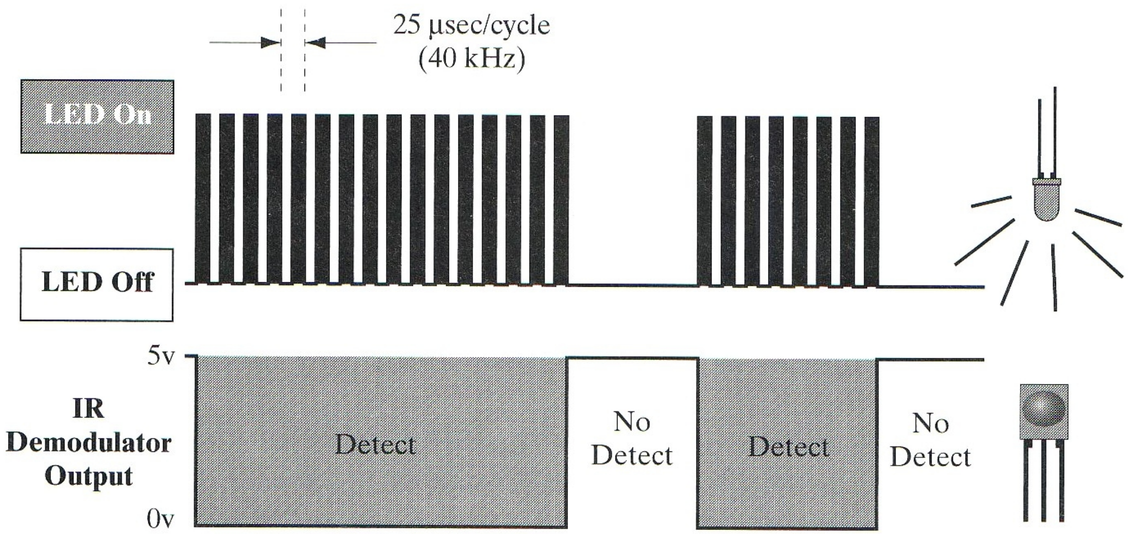
- **Reflective Sensor:**
  - Emitter IR LED + detector photodiode/phototransistor
  - Phototransistor: the more light reaching the phototransistor, the more current passes through it
  - A beam of light is reflected off a surface and into a detector
  - Light usually in infrared spectrum, IR light is invisible
- **Applications:**
  - Object detection,
  - Line following, Wall tracking
  - Optical encoder (Break-Beam sensor)



- **Drawbacks:**
  - Susceptible to ambient lighting
  - Susceptible to reflectivity of objects
  - Susceptible to the distance between sensor and the object

Modulated Infrared

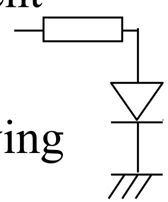
- **Modulation and Demodulation**
  - Flashing a light source at a particular frequency
  - Demodulator is tuned to the specific frequency of light flashes. (32kHz~45kHz)
  - Flashes of light can be detected even if they are very week
  - Less susceptible to ambient lighting and reflectivity of objects
  - Used in most IR remote control units, proximity sensors

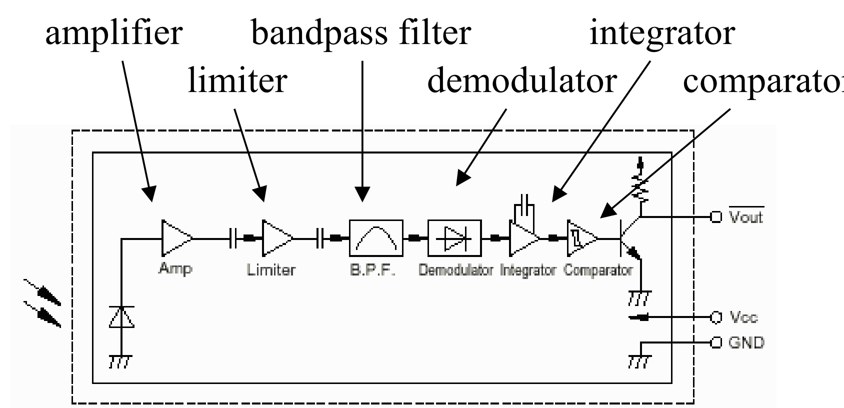


IR Proximity Sensors

- **Proximity Sensors:**
  - Requires a modulated IR LED, a detector module with built-in modulation decoder
  - Current through the IR LED should be limited: adding a series resistor in LED driver circuit
  - Detection range: varies with different objects (shiny white card vs. dull black object)
  - Insensitive to ambient light

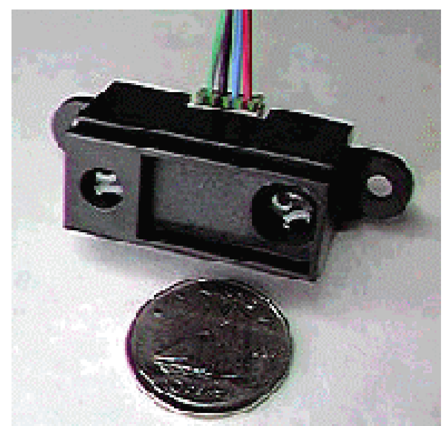
- **Applications:**
  - Rough distance measurement
  - Obstacle avoidance
  - Wall following, line following





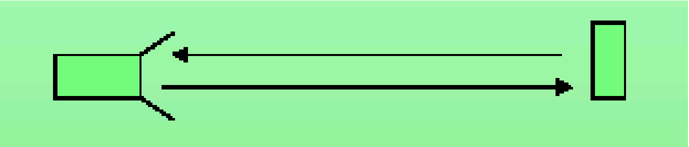
IR Distance Sensors

- **Sharp GP2D02 IR Ranger**
  - Distance range: 10cm (4") ~ 80cm (30").
  - Moderately reliable for distance measurement
  - Immune to ambient light
  - Impervious to color and reflectivity of object
  - Applications: distance measurement, wall following, …



Range Finder

- **Time of Flight**



- **The measured pulses typically come form ultrasonic, RF and optical energy sources.**
  - **$D = v * t$**
  - D = round-trip distance
  - v = speed of wave propagation
  - t = elapsed time
- **Sound = 0.3 meters/msec**
- **RF/light = 0.3 meters / ns (Very difficult to measure short distances 1-100 meters)**

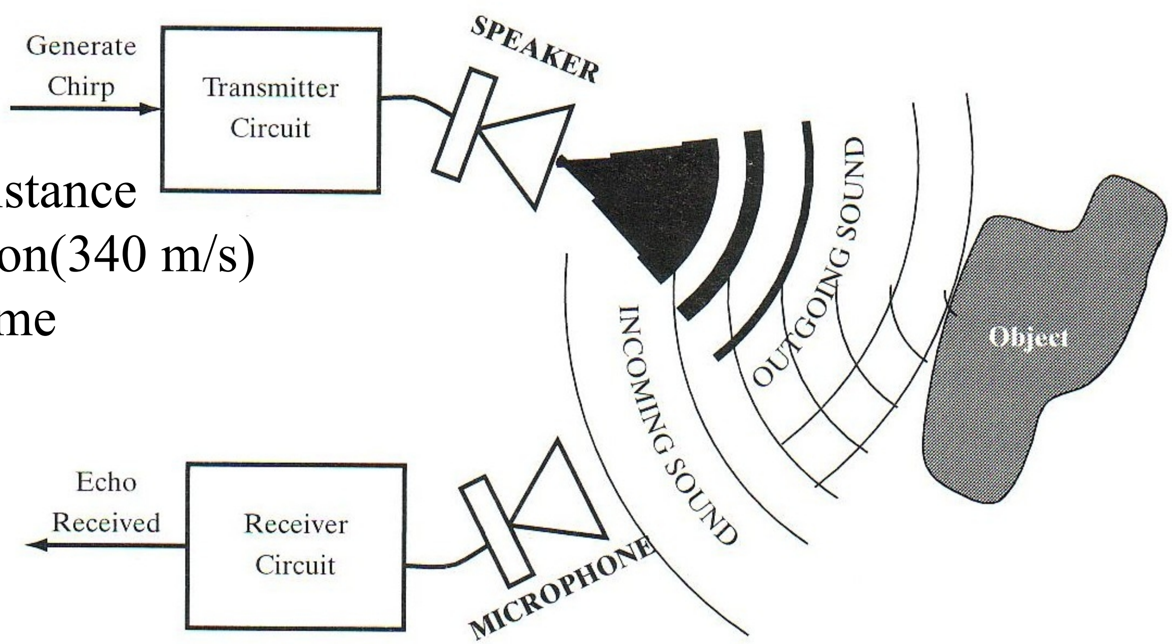
Ultrasonic Sensors

- **Basic principle of operation:**
  - Emit a quick burst of ultrasound (50kHz), (human hearing: 20Hz to 20kHz)
  - Measure the elapsed time until the receiver indicates that an echo is detected.
  - Determine

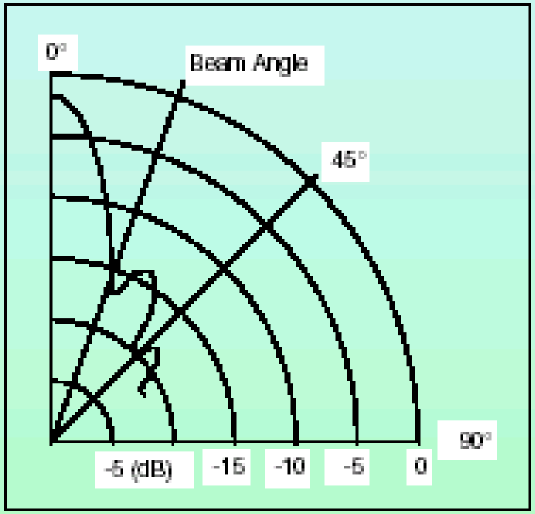
- **D = v * t**

D = round-trip distance
v = speed of propagation(340 m/s)
t = elapsed time

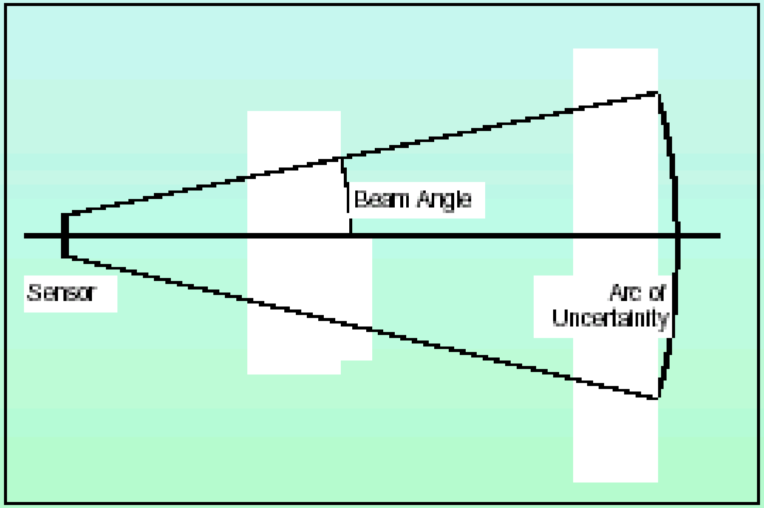
Bat, dolphin, …



Ultrasonic Sensors



Sensor Specification



Sensor Model, angle = 15 degrees

- **Ranging is accurate but bearing has a 30 degree uncertainty. The object can be located anywhere in the arc.**
- **Typical ranges are of the order of several centimeters to 30 meters.**
- **Another problem is the propagation time. The ultrasonic signal will take 200 msec to travel 60 meters. (30 meters roundtrip @ 340 m/s)**

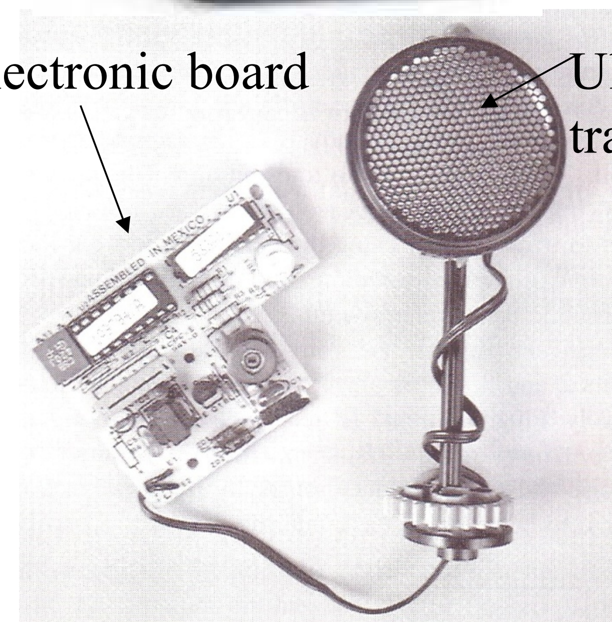
Polaroid Ultrasonic Sensors

– It was developed for an automatic camera focusing system

– Range: 6 inches to 35 feet

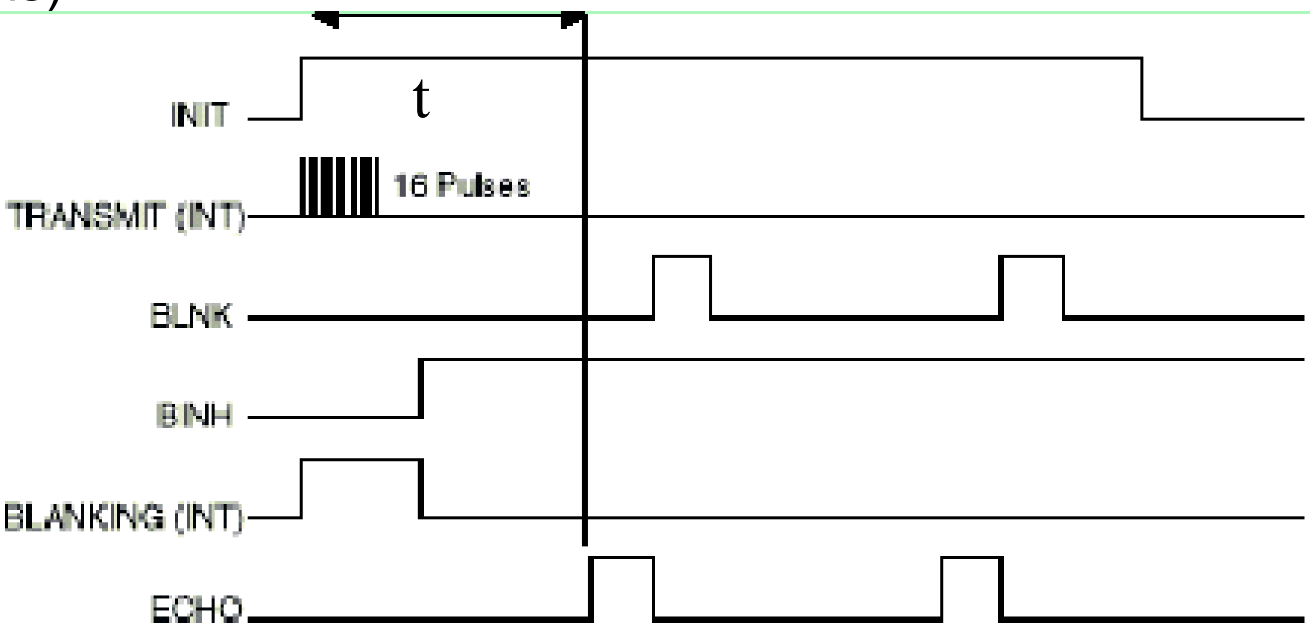
Transducer Ringing:

- transmitter + receiver @ 50 KHz
- Residual vibrations or ringing may be interpreted as the echo signal
- Blanking signal to block any return signals for the first 2.38ms after transmission



Operation with Polaroid Ultrasonic

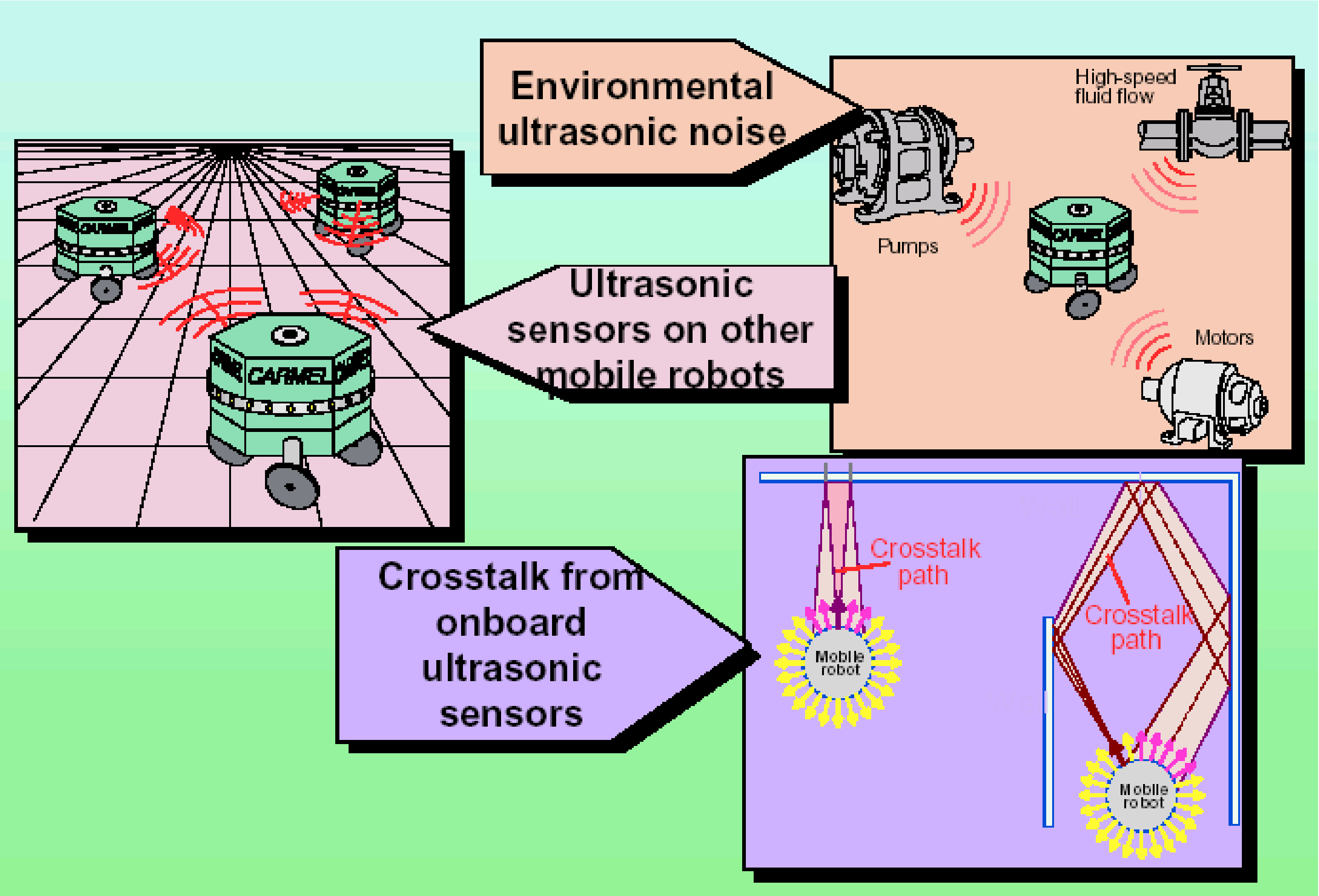
- **The Electronic board supplied has the following I/0**
  - **INIT** : trigger the sensor, (16 pulses are transmitted)
  - **BLANKING** : goes high to avoid detection of own signal
  - **ECHO** : echo was detected.
  - **BINH** : goes high to end the blanking (reduce blanking time < 2.38 ms)
  -



Ultrasonic Sensors

- **Applications:**
  - Distance Measurement
  - Mapping: Rotating proximity scans (maps the proximity of objects surrounding the robot)

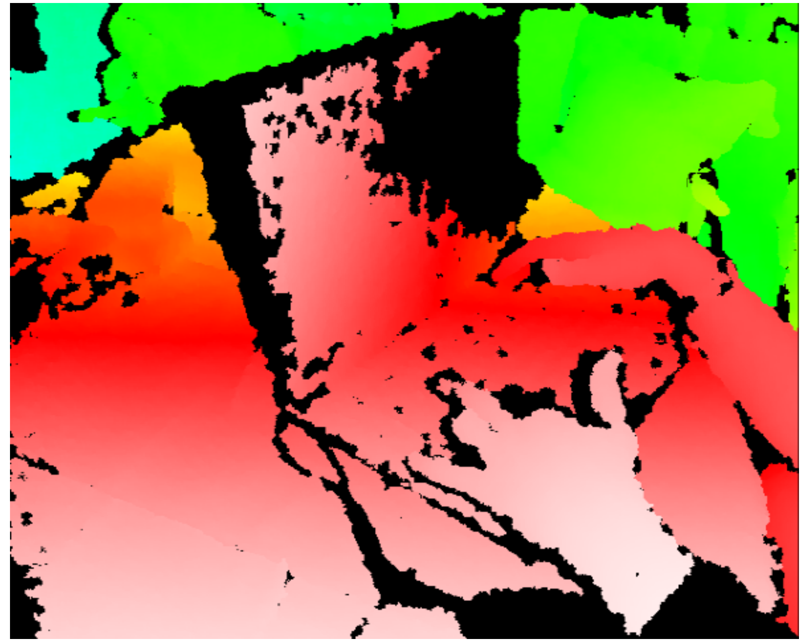
Noise Issues



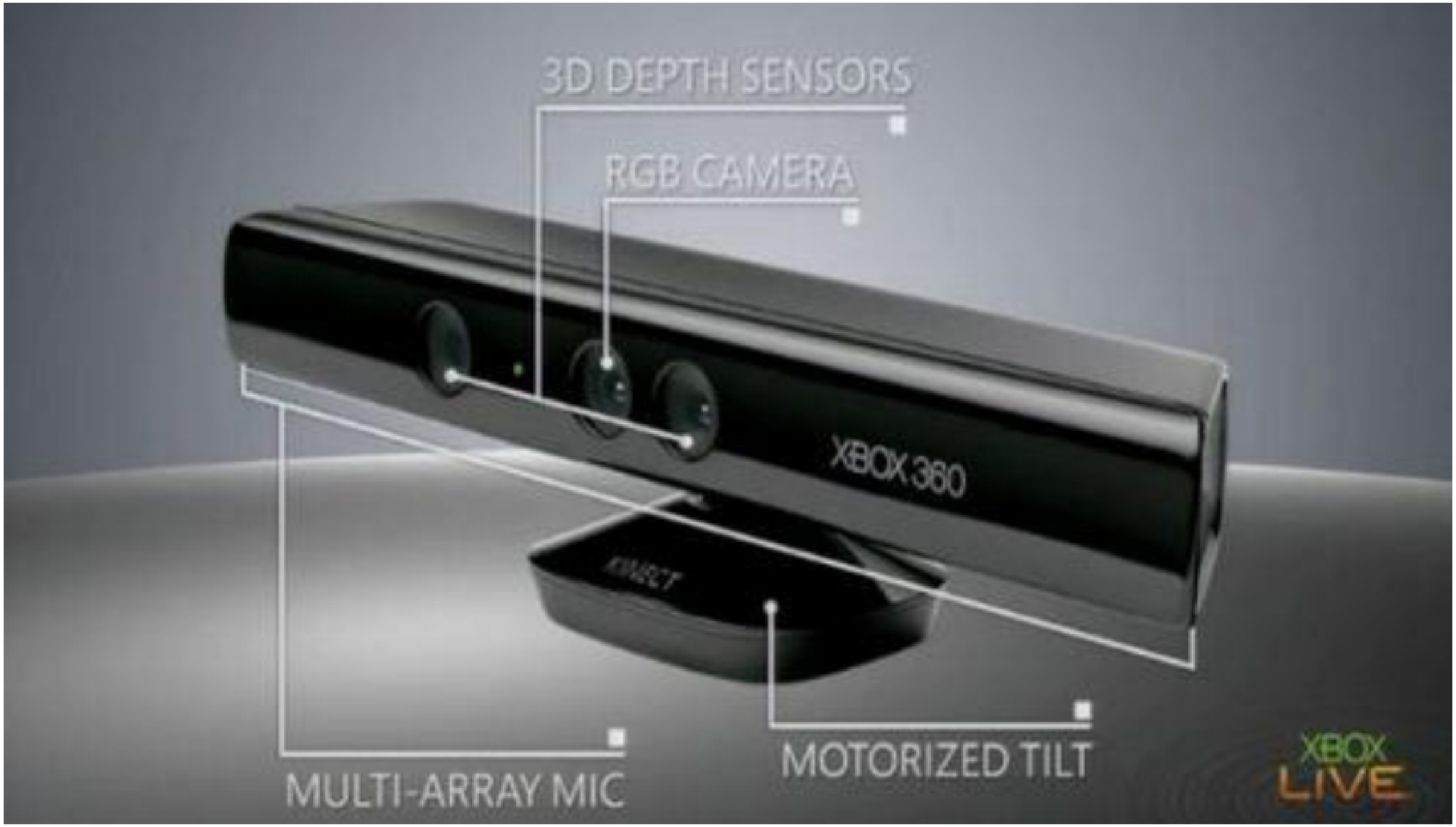
Laser Ranger Finder

- Range 2-500 meters
- Resolution : 10 mm
- Field of view : 100 - 180 degrees
- Angular resolution : 0.25 degrees
- Scan time : 13 - 40 msec.
- These lasers are more immune to Dust and Fog

Cameras & Range Cameras: Kinect



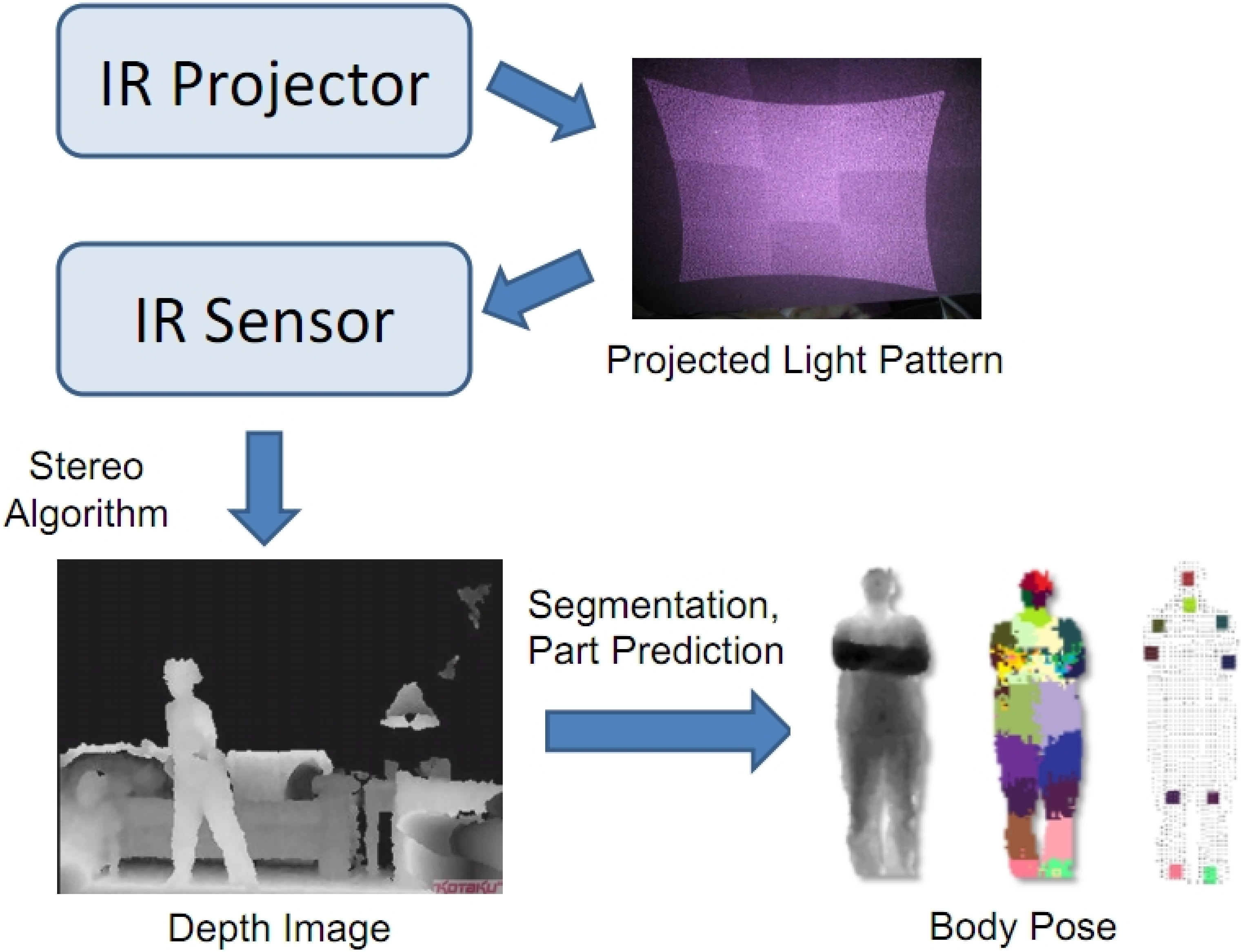
Kinect


3D DEPTH SENSORS
RGB CAMERA
XBOX 360
MULTI-ARRAY MIC
MOTORIZED TILT
XBOX
LIVE

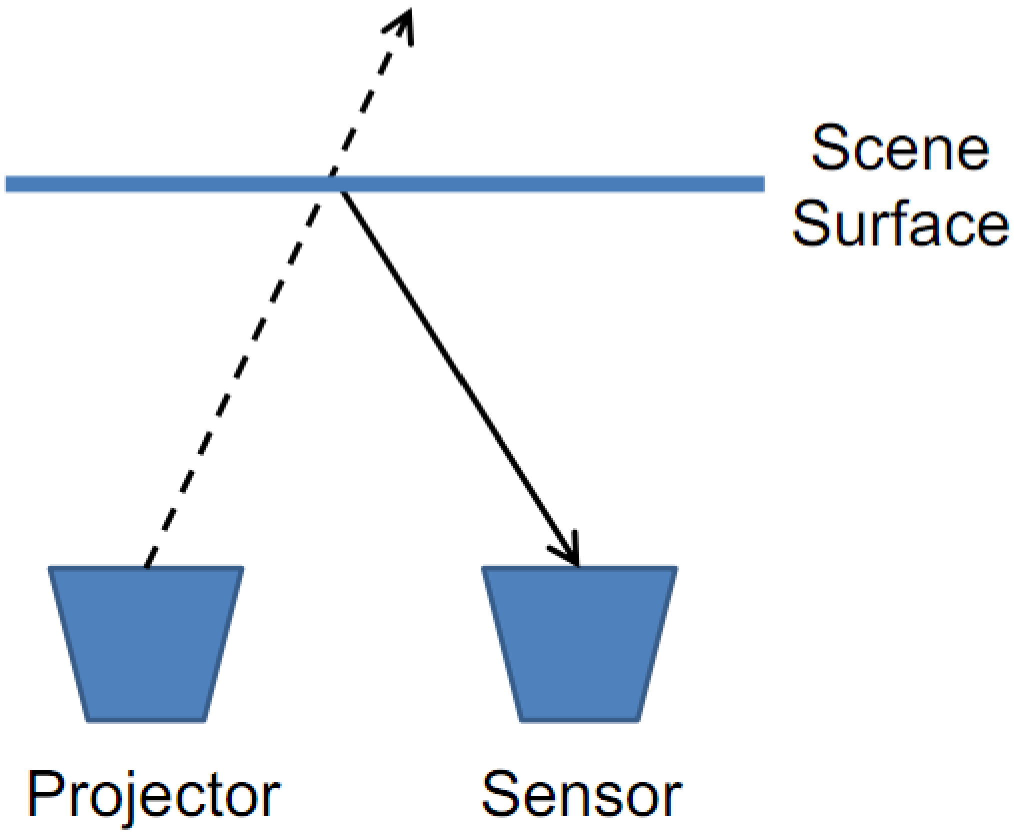
Kinect

Depth Image
3 PS1080 SoC
1 IR Light Source
Scene projected by invisible IR Light
2 Standard CMOS Sensor
Sensing Device
Scene

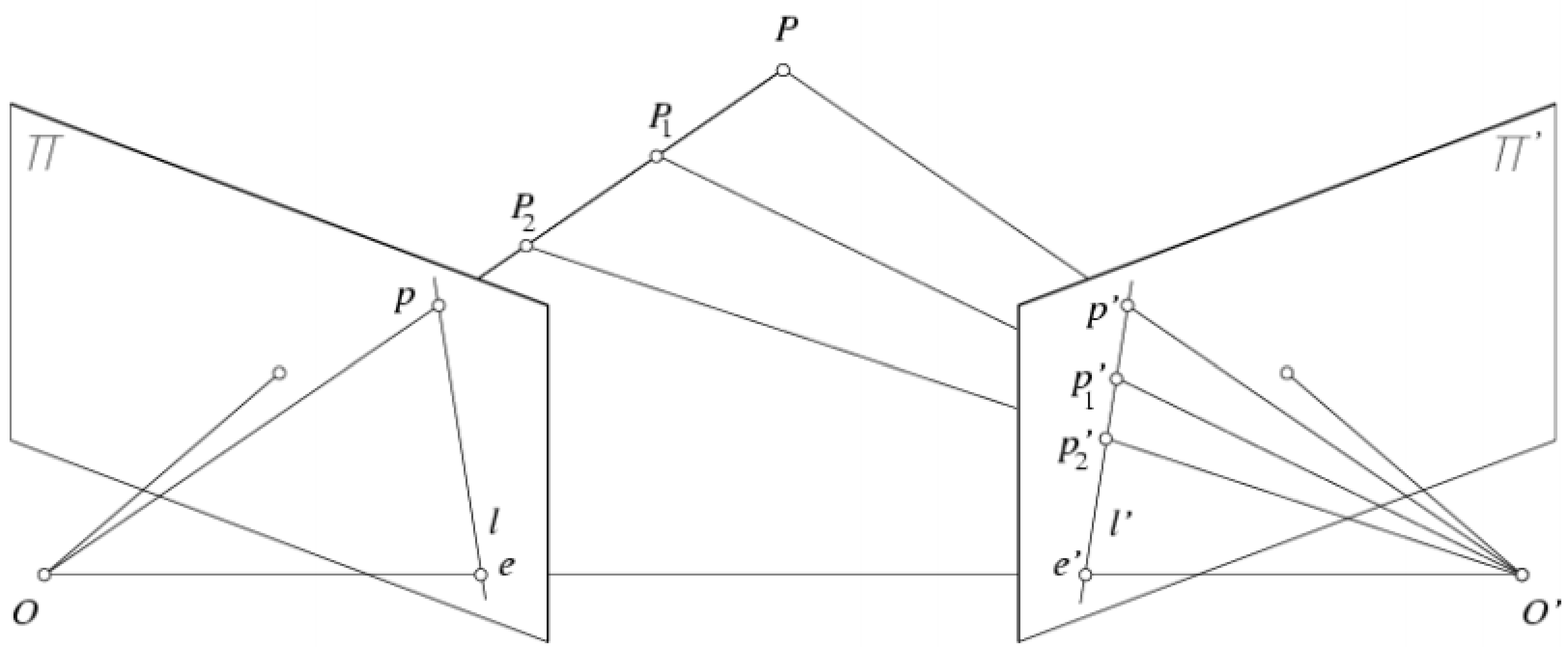
Kinect


IR Projector
Projected Light Pattern
IR Sensor
Stereo
Algorithm
Segmentation,
Part Prediction
Depth Image
Body Pose

Kinect



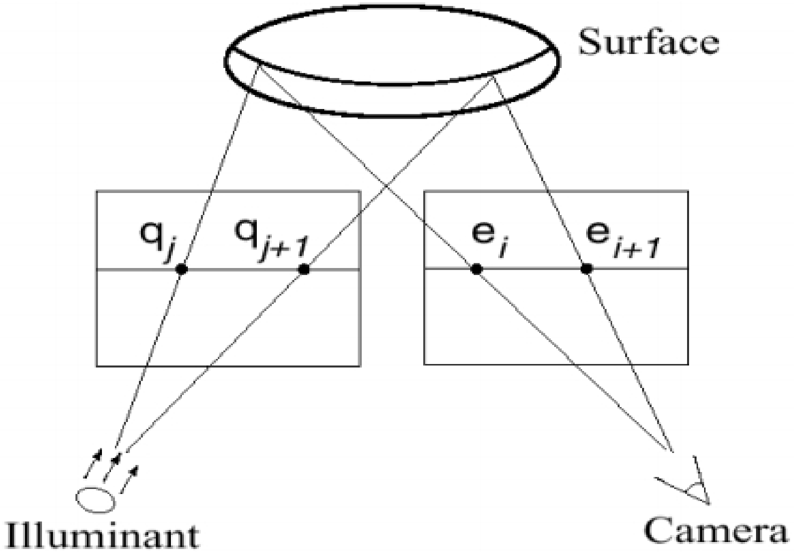
Kinect – Stereo Algorithm

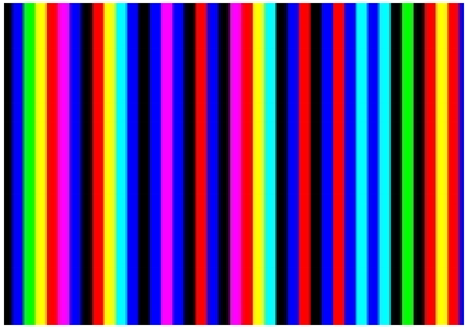


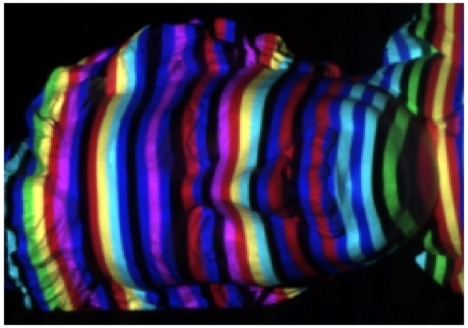
Projector

Sensor

Active Stereo with structured light







L. Zhang, B. Curless, and S. M. Seitz. Rapid Shape Acquisition Using Color Structured Light and Multi-pass Dynamic Programming. *3DPVT* 2002

Slide credit: S. Seitz

Noise Issues

- **Real sensors are noisy**
- **Origins: natural phenomena + less-than-ideal engineering**
- **Consequences: limited accuracy and precision of measurements**
- **Filtering:**
  - software: averaging, signal processing algorithm

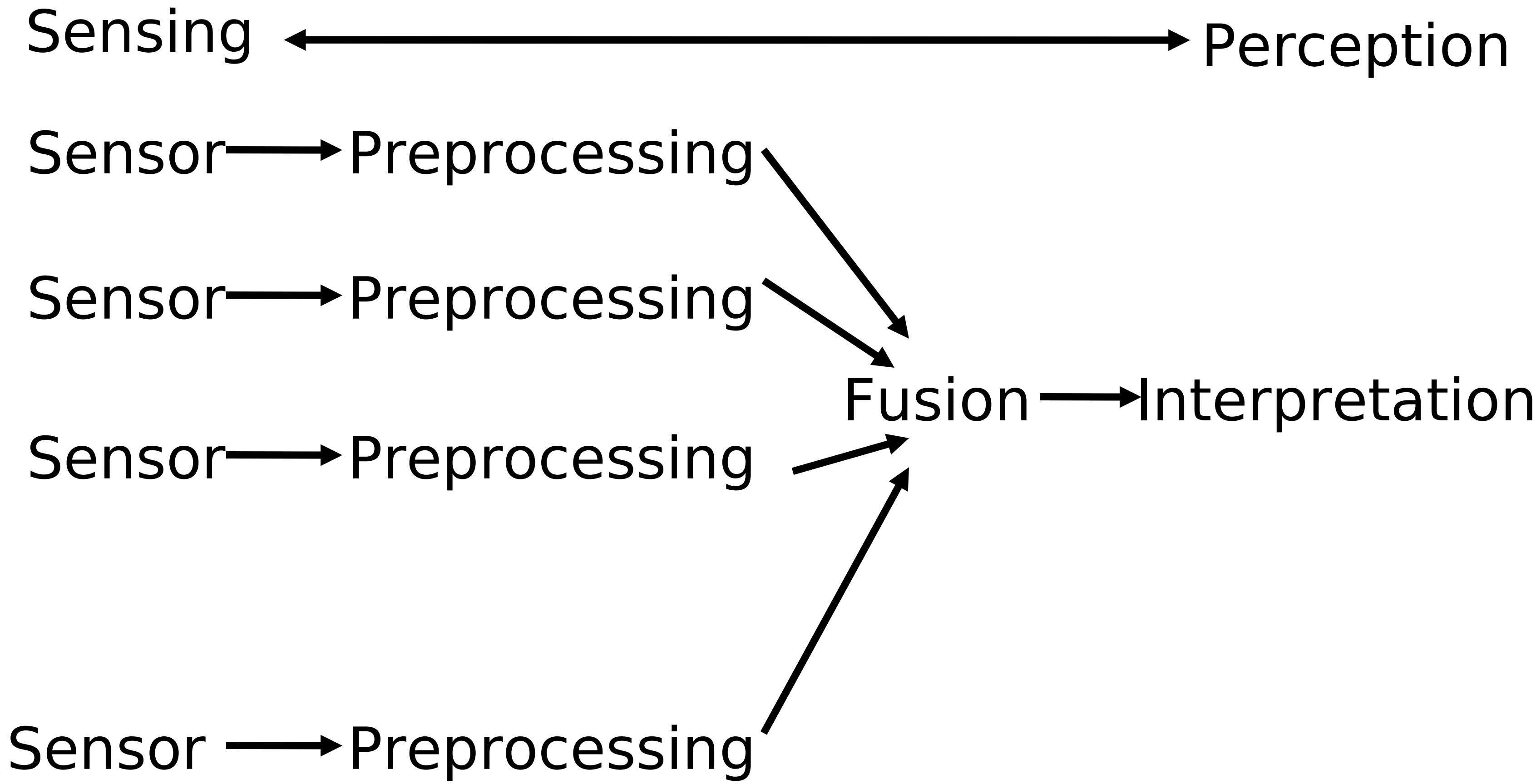
Sensor Fusion and Integration

- **Human: One organ ⇔one sense?**
  - Not necessarily
    - Balance: ears
    - Touch: tongue
    - Temperature: skin
- **Robot:**
  - Sensor fusion:
    - Combine readings from several sensors into a (uniform) data structure
  - Sensor integration:
    - Use information from several sensors to do something useful

Sensor Fusion

- **One sensor is (usually) not enough**
  - Real sensors are noisy
  - Limited Accuracy
  - Unreliable - Failure/redundancy
  - Limited point of view of the environment
    - Return an incomplete description of the environment
  - The sensor of choice may be expensive - might be cheaper to combine two inexpensive sensors

General Processing



Preprocessing

- Colloquially - ‘cleanup’ the sensor readings before using them
- Noise reduction - filtering
- Re-calibration
- ‘Basic’ stuff - e.g. edge detection in vision
- Usually unique to each sensor
- Change (transform) data representation

Sensor/Data Fusion

- **Combine data from different sources**
  - measurements from different sensors
  - measurements from different positions
  - measurements from different times
- **Often a mathematical technique that takes into account uncertainties in data sources**
  - Discrete Bayesian methods
  - Neural networks
  - Kalman & Particle filtering
- **Produces a merged data set (as though there was one ‘virtual sensor’)**

Readings

- **A Benchmark *Test* for Measuring Odometry Errors in Mobile *Robots, by* J. Borenstein**

- **UMBmark -- A Method for Measuring, Comparing, and Correcting Odometry Errors in Mobile Robots, by Johann Borenstein(1) and Liqiang Feng(2), December 1994, [Online] http://www personal.umich.edu/~johannb/umbmark.htm**

- **http://robots.net/article/2758.html**