RBE 2002: Unified Robotics II
Survey of Sensors

Prof. Putnam

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MEASUREMENTS, INSTRUMENTATION AND SENSORS

Definitions

- ✓ An ***instrument*** is a device that transforms a physical variable of interest into a form that is suitable for recording
- ✓ The ***sensor*** has the function of converting the *physical variable input* into a *signal variable output*
- ✓ ***Transducers*** are devices that convert input energy of one form into output energy of another form.
  - Sensors are input transducers (e.g., photoresistor)
  - Actuators are output transducers (e.g., motors)

In Robotics

- ✓ Sensing
  - Transformation of physical entities such as contact, force, distance, light intensity, etc. into an internal computer representation
    - *Electronics*
    - *Signal processing*
    - *Computation*
- ✓ Perception
  - The extraction of key properties from the sensory data and integration of sensory information over time
    - *Edges, lines, planes*
    - *Histograms*
    - *Map generation*

Sensor Classification

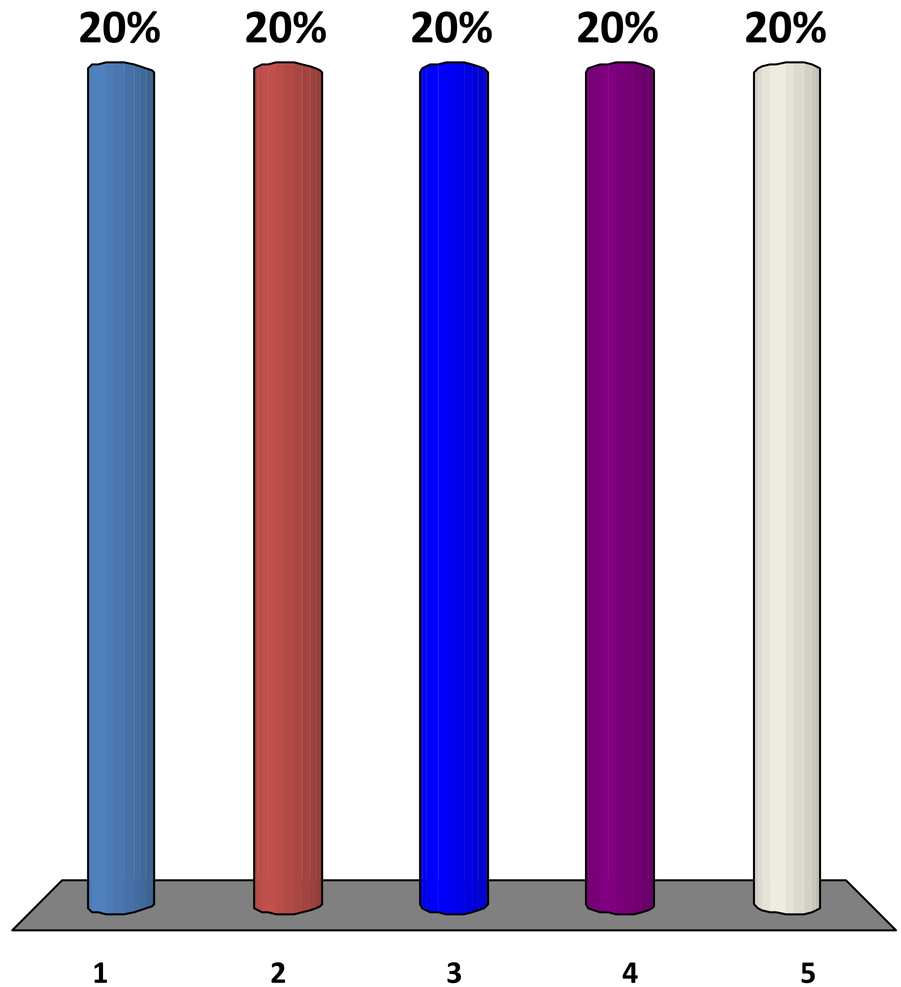
- ✓ Proprioceptive sensors
  - Measure values internal to the robot
    - *Position of the wheels*
      - *Steering angle*
      - *Rocker-bogie angles*
      - *Wheel shaft angle*
    - *Motor speed*
    - *Motor current*
    - *Robot arm joint angles*
    - *Battery voltage*
    - *Internal temperature*
    - *Fuel remaining*

Sensor Classification

- ✓ Exteroceptive sensors
  - Acquire information from the robot’s environment
    - *Distance measurements*
    - *Light intensity*
    - *Sound amplitude*
    - *Bearing to a sound/light/heat/… source*

Which sensor on Curiosity was damaged during landing?

1. Left-front Nav camera
2. Left-rear Nav camera
3. Wind sensor
4. MAHLI (Mars Hand Lens Imager)
5. No idea…



Sensor Classification

- ✓ Passive sensors
  - Measure ambient environmental energy entering the sensor
  - *Temperature probes, contact switches, microphones, CCD or CMOS image sensors (cameras)*

- ✓ Active sensors
  - Emit energy into the environment, then measure the reaction
  - *Ultrasonic sensors, laser rangefinders*
  - Often have superior performance
  - Issues with signal interference

Sensor Classification

Sensor	Use	PC or EC	P or A
Switches	Tactile sensing		
Noncontact proximity sensors	Tactile sensing		
Encoders	Motor position/speed		
Potentiometers	Position		
Compass	Orientation		
Gyroscope	Orientation		
GPS	Localization		
Ultrasonic	Ranging		
Lidar	Ranging		
CCD/CMOS camera	Image capture		

Sensor Performance

- ✓ Dynamic range
  - Used to measure the spread between the lower and upper limits of input values to the sensor while maintaining normal sensor operation
  - Dynamic range = Maximum input / Minimum measurable input
  - Often measured in dB

Sensor Performance

✓ Resolution

- The smallest increment in the measured value that can be discerned
- Can also be thought of as the least count (or the least significant digit) of the output indicator

SENSOR CHARACTERISTICS

Sensor Characteristics

- ✓ The dynamic range of inputs which may be converted by a sensor is called the ***span*** or ***full-scale input (FSI)***
- ✓ ***Full-scale output (FSO)*** is the algebraic difference between the electrical output signals measured with maximum input and the lowest input stimulus applied

$$FSO = y_{\max} - y_{\min} = r_o$$

- ✓ A very important characteristic of a sensor is ***accuracy*** which really means inaccuracy. Inaccuracy is measured as a highest deviation of a value represented by the sensor from the ideal or true value at its input.

Sensor Characteristics

- ✓ ***Calibration*** means the determination of specific variables that describe the overall transfer function
- ✓ There may be many variables that affect how the input to the sensor is reflected in the output

Sensor Characteristics

- ✓ ***Transfer Function:*** An ideal or theoretical input-output relationship exists for every sensor

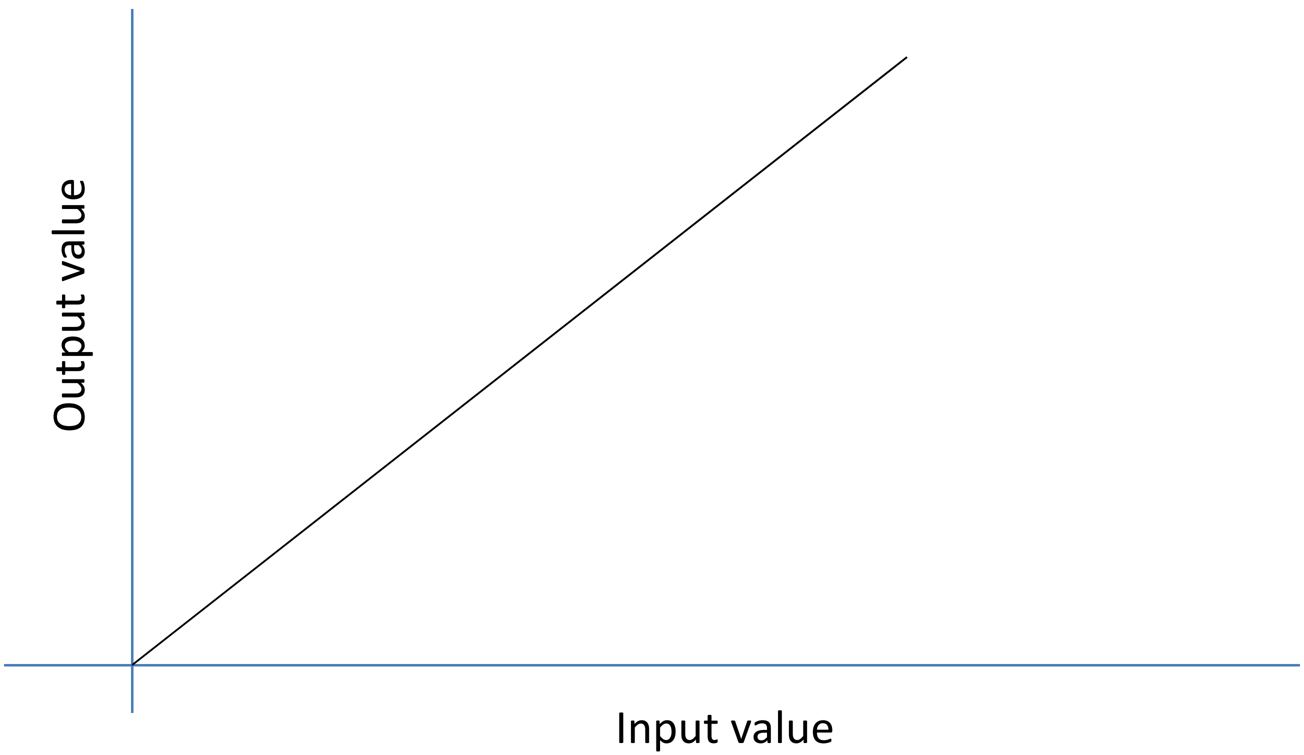
$$y = f(x)$$

- ✓ Examples:

$$\begin{aligned} y &= ax + b \\ y &= a + b \ln x \\ y &= ae^{kx} \\ y &= a_0 + a_1 x^k \end{aligned}$$

Sensor Characteristics

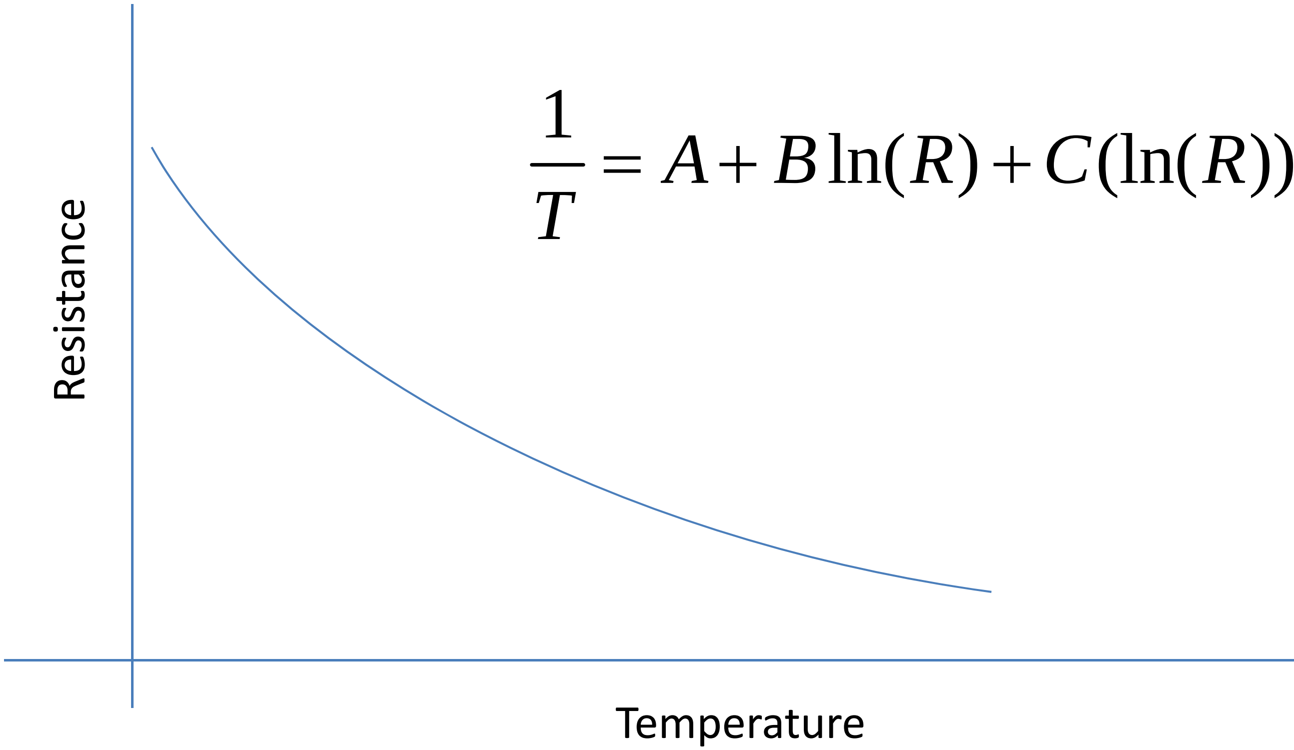
✓ In this case we show a nice linear relationship between the input and output values



Sensor Characteristics

- ✓ This is the typical calibration curve for a negative temperature coefficient thermistor
- ✓ You might use the Steinhart-Hart equation to represent this curve

$$\frac{1}{T} = A + B\ln(R) + C(\ln(R))^3$$

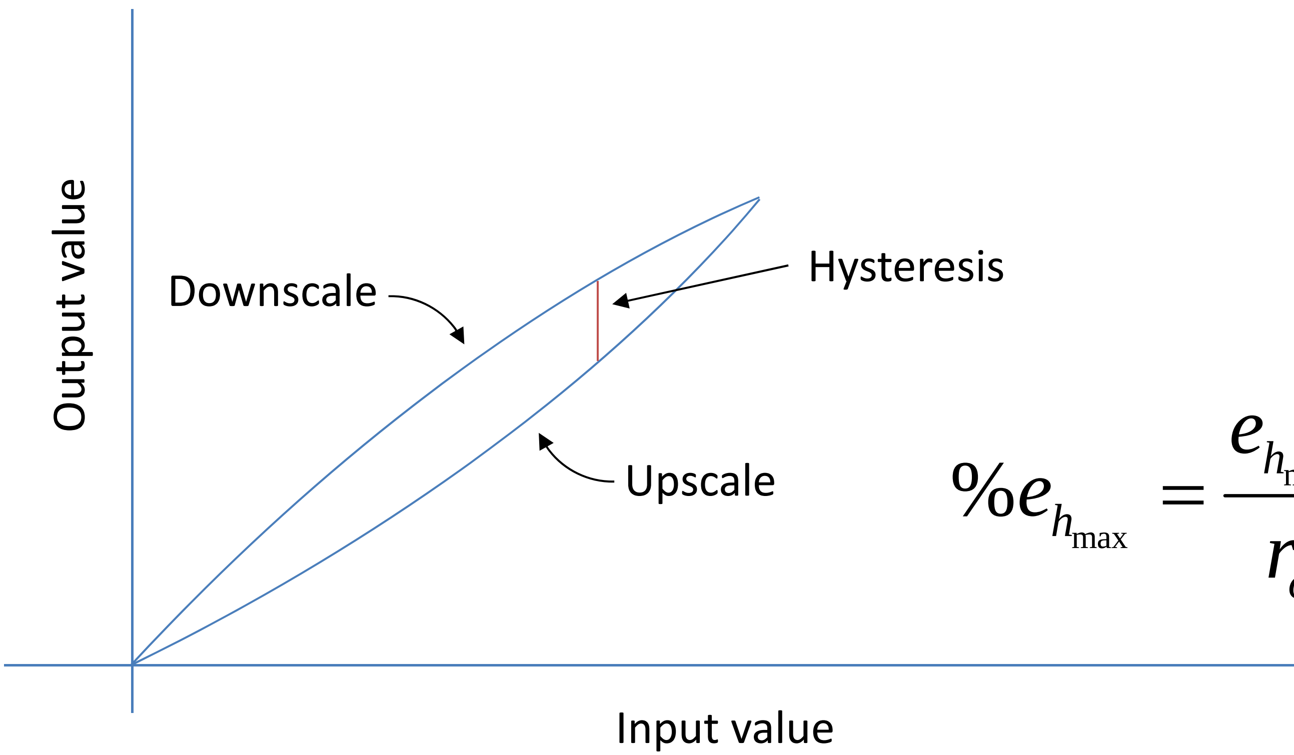


Sensor Characteristics

- ✓ ***Calibration*** means the determination of specific variables that describe the overall transfer function
- ✓ There may be many variables that affect how the input to the sensor is reflected in the output
- ✓ Because there are many variables, there are many possible sources of errors…

Sensor Characteristics

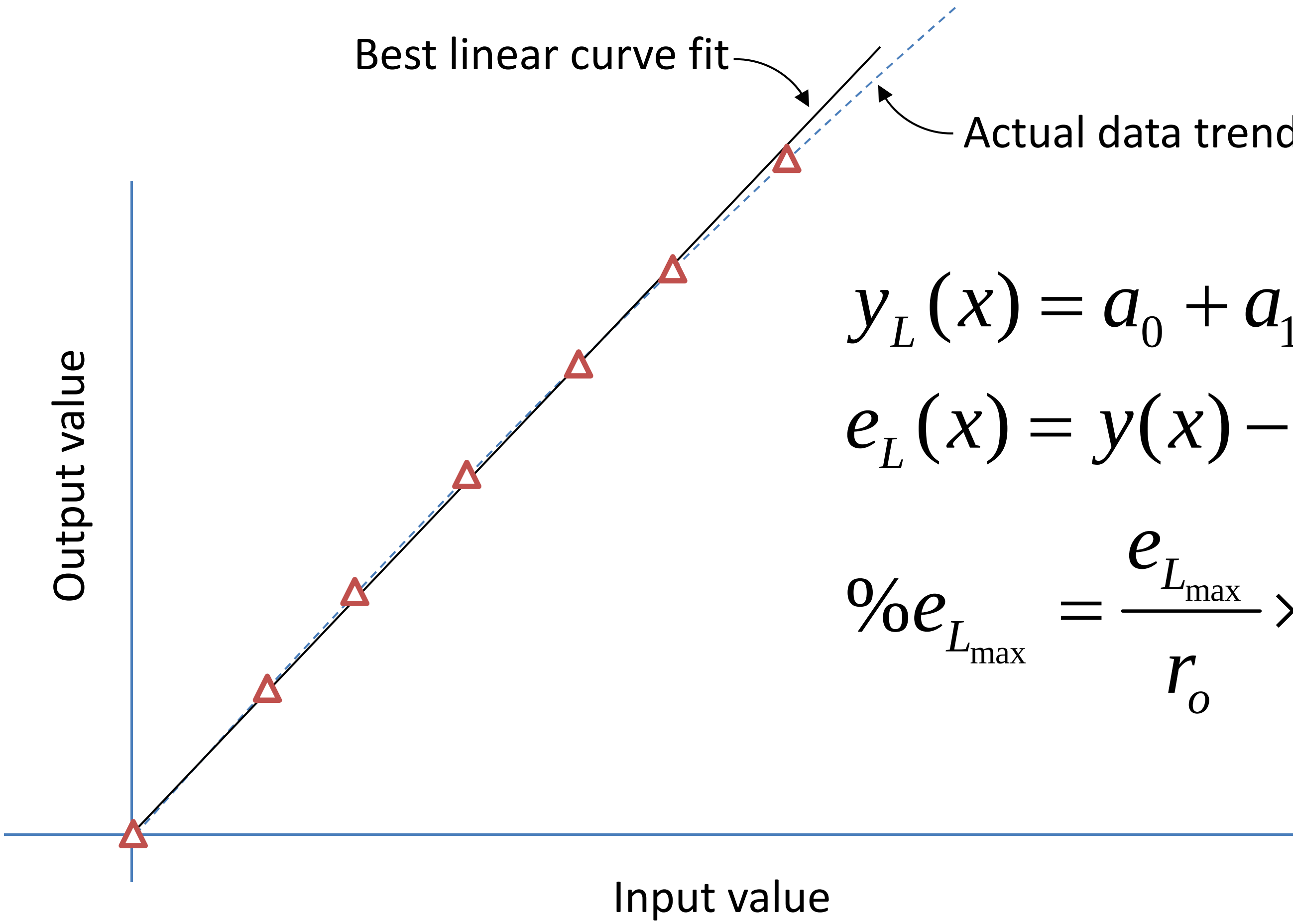
- ✓ A ***hysteresis error*** is a deviation of the sensor's output at a specified point of the input signal when it is approached from the opposite directions



$$\%e_{h_{\max}} = \frac{e_{h_{\max}}}{r_o} \times 100$$

Sensor Characteristics

- ✓ ***Nonlinearity error*** is specified for sensors whose transfer function may be approximated by a straight line



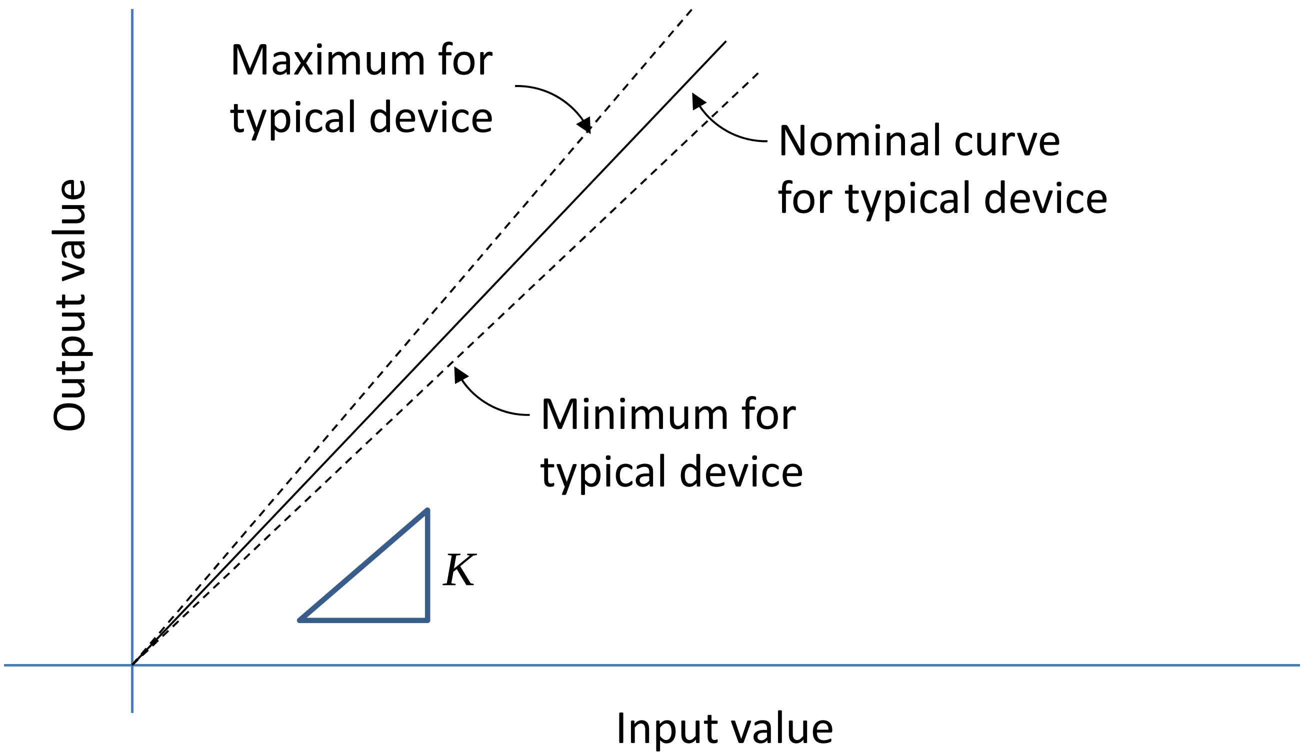
$$y_L(x) = a_0 + a_1 x$$

$$e_L(x) = y(x) - y_L(x)$$

$$\%e_{L_{\max}} = \frac{e_{L_{\max}}}{r_o} \times 100$$

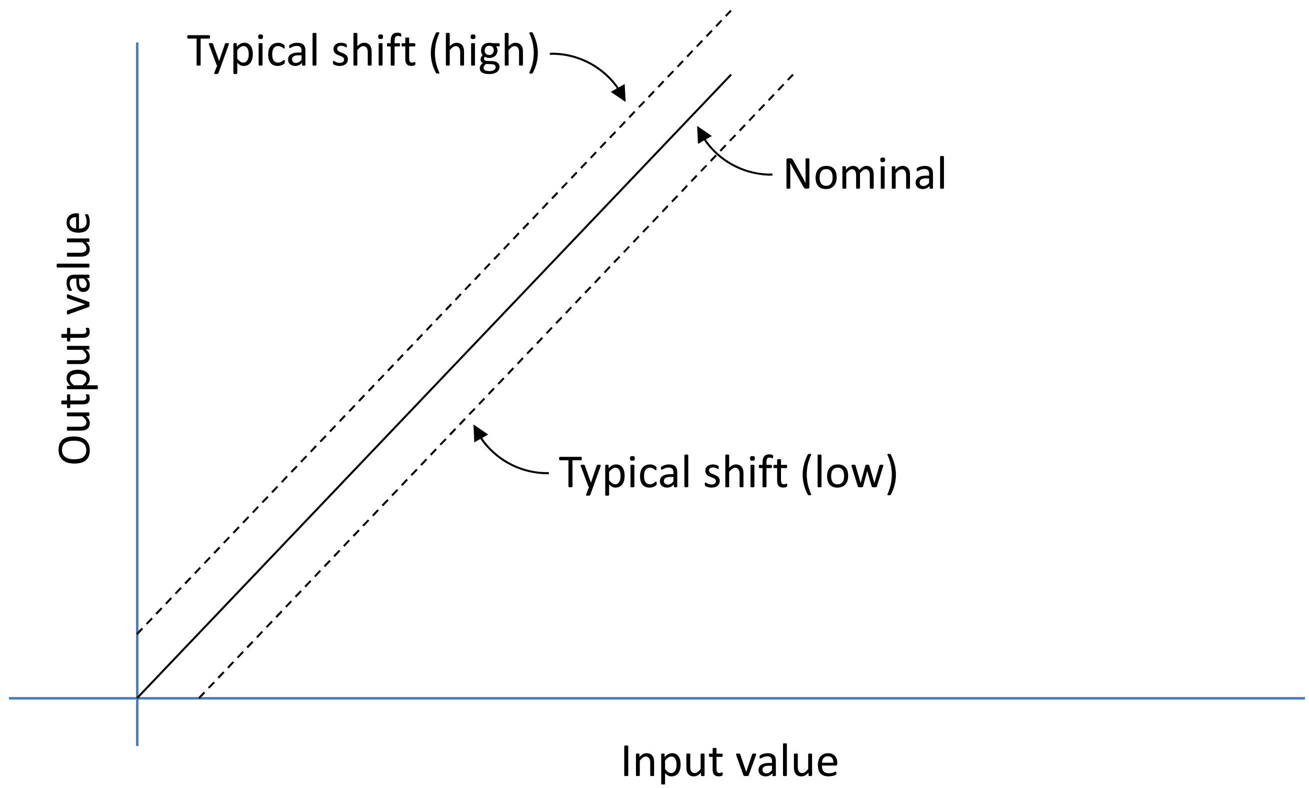
Sensor Characteristics

✓ ***Sensitivity error*** (e_K) is a statistical measure of the random error in the estimate of the slope of the calibration curve



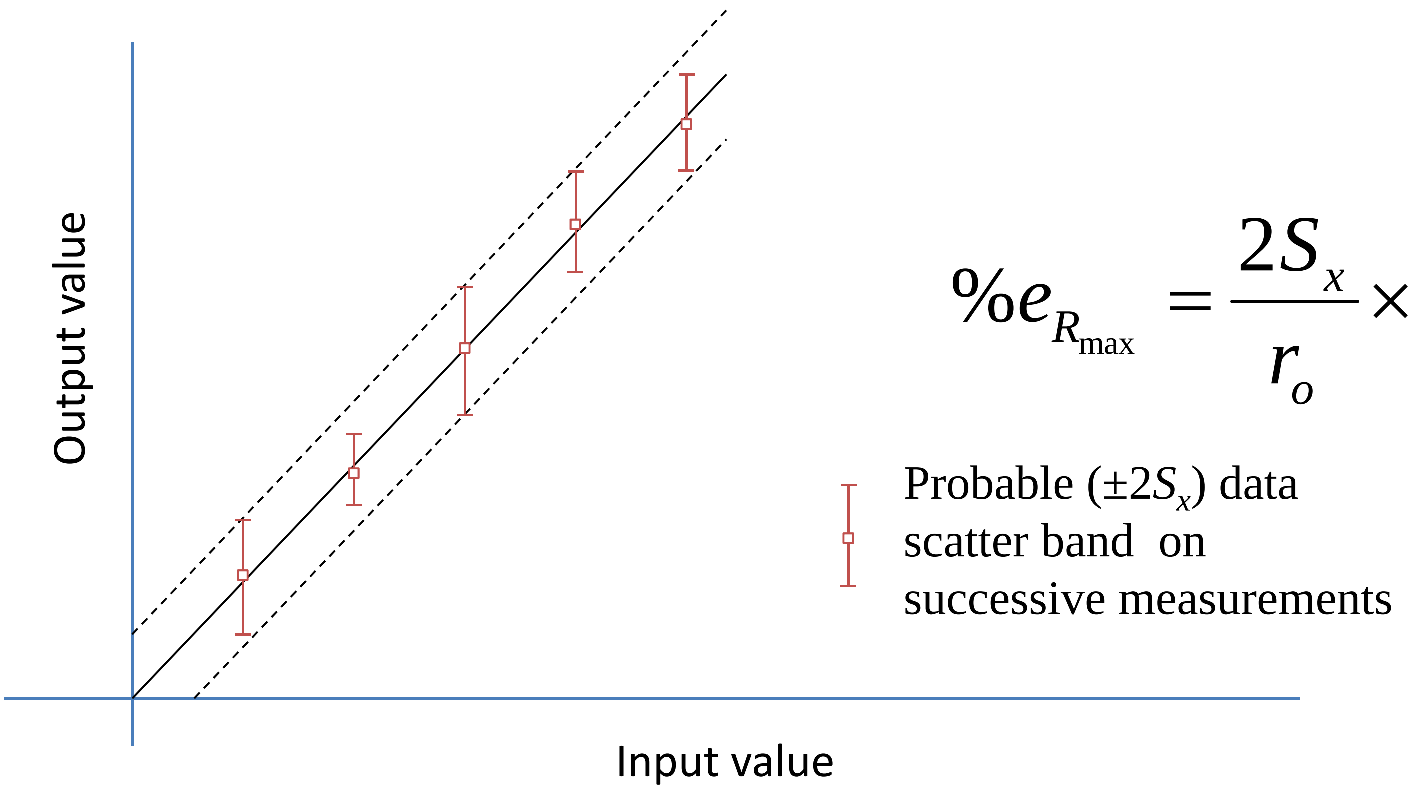
Sensor Characteristics

✓ ***Zero shift (null) error*** (e_Z) happens when the sensitivity is constant but the zero intercept is not fixed



Sensor Characteristics

- ✓ ***Repeatability error*** happens when the sensitivity is constant but the zero intercept is not fixed



$$\%e_{R_{\max}} = \frac{2S_x}{r_o} \times 100$$

Sensor Characteristics

- ***Overall instrument error*** or ***uncertainty*** is calculated by combining all of the known errors
- This is also sometimes misleadingly called the instrument accuracy
- For M known error sources, the uncertainty is estimated as:

$$u_c = \sqrt{e_1^2 + e_2^2 + \ldots + e_M^2}$$

- For example, for an instrument with known hysteresis, linearity, and sensitivity errors, we have:

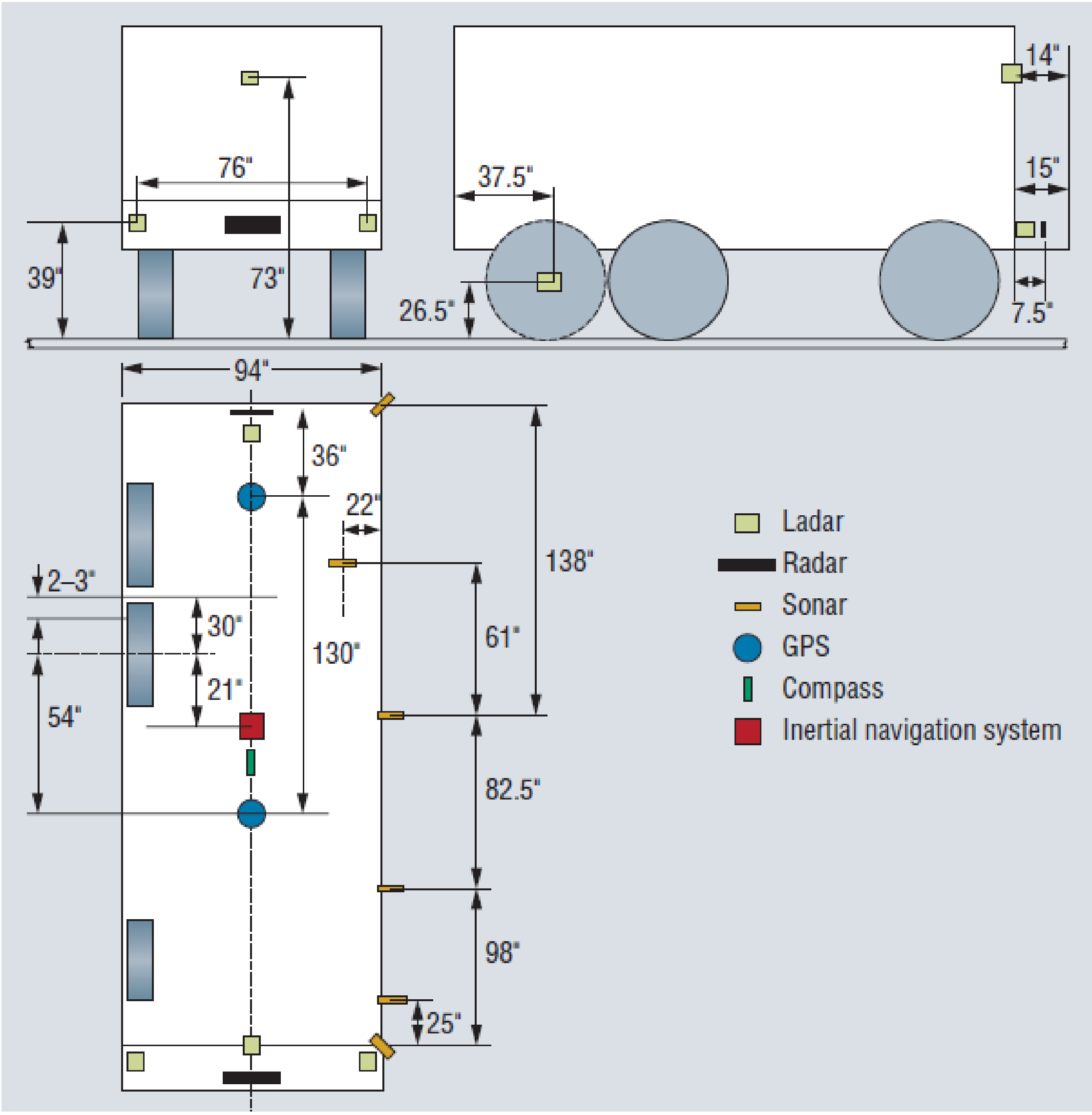
$$u_c = \sqrt{e_h^2 + e_L^2 + e_K^2}$$

Sensor Characteristics

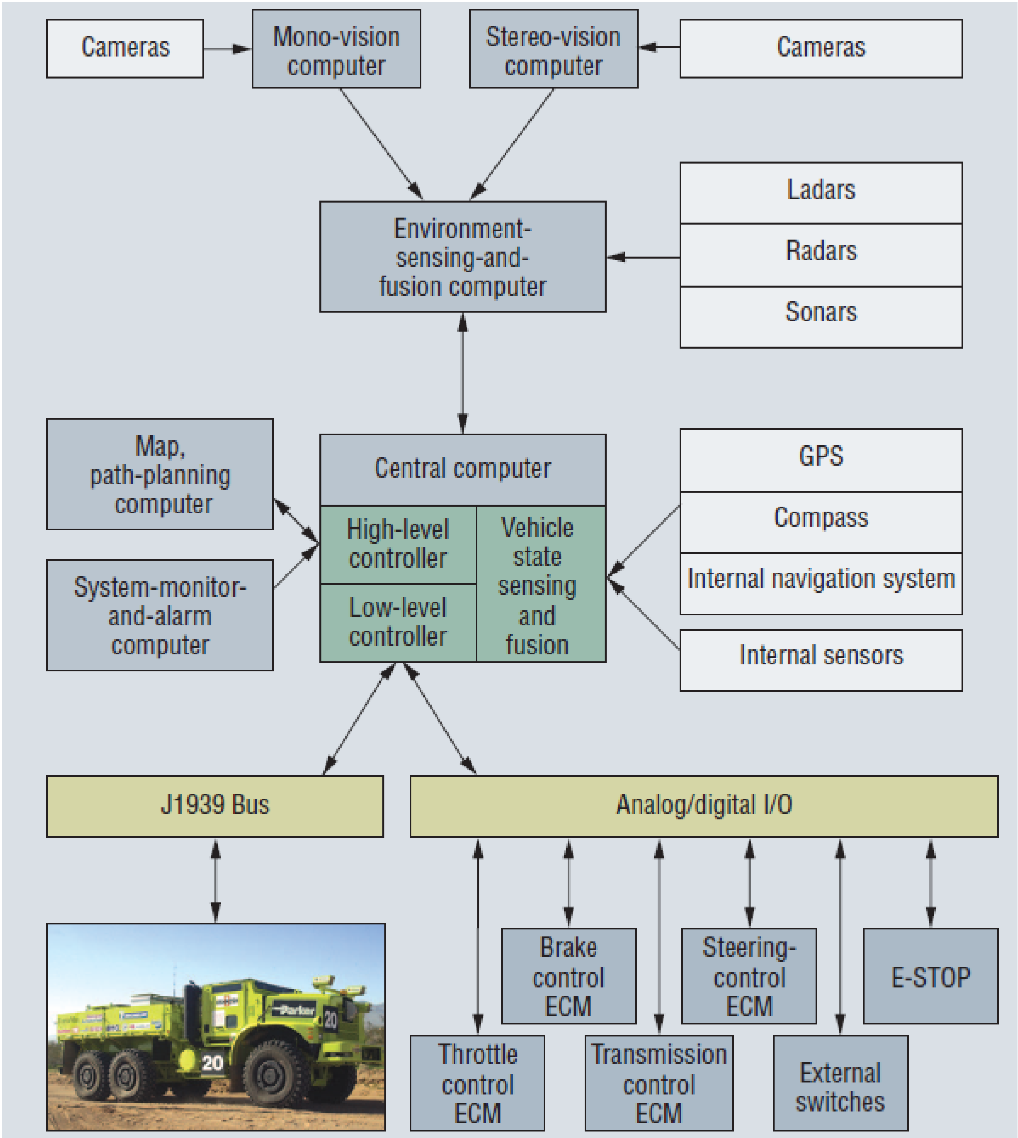
- ✓ ***Saturation***
- ✓ ***Repeatability***
- ✓ ***Dead Band***
- ✓ ***Resolution***
- ✓ ***Output Impedance***
- ✓ ***Excitation***
- ✓ ***Dynamic Characteristics***

The TerraMax Vehicle

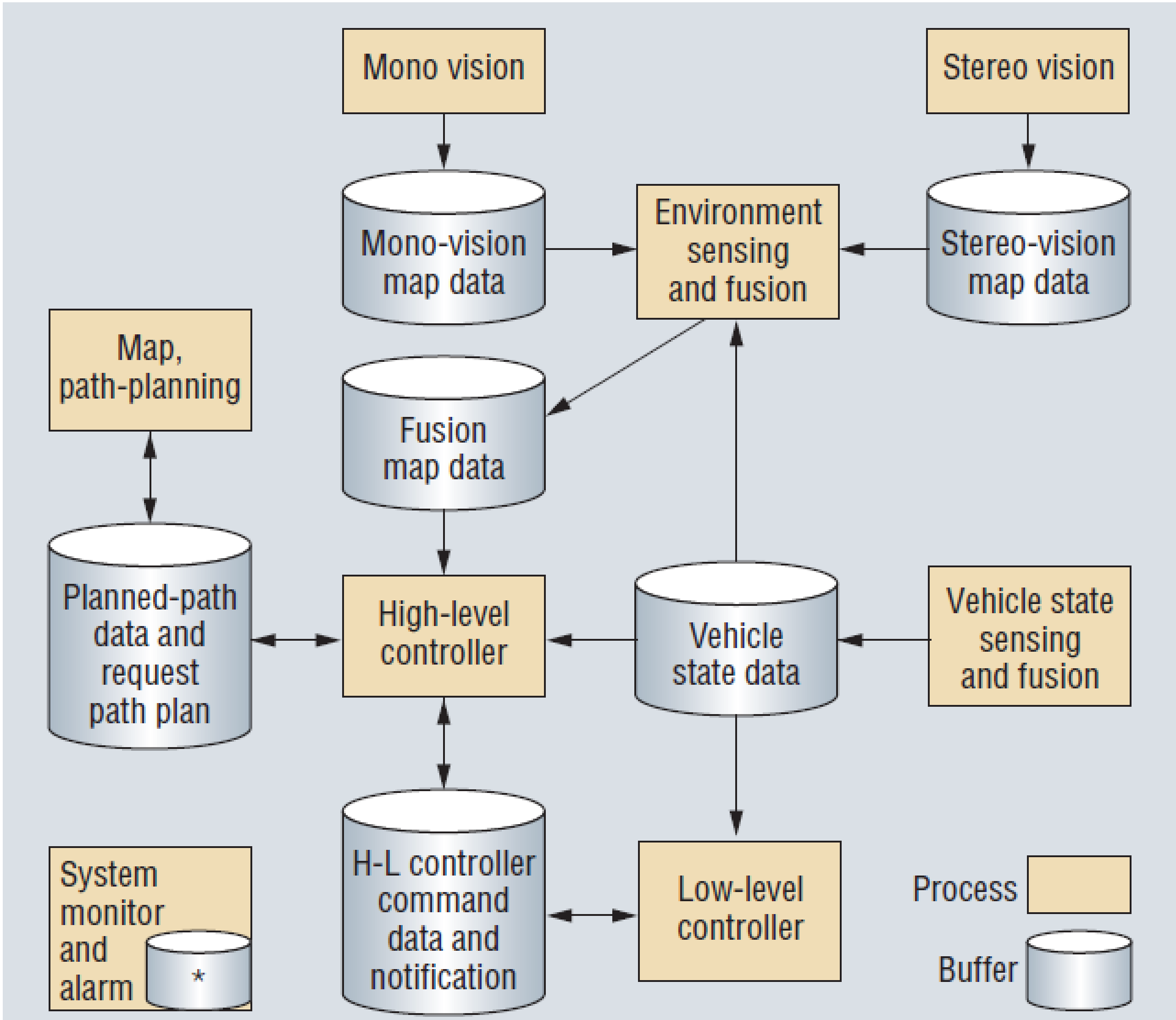
Mounting of the Sensors



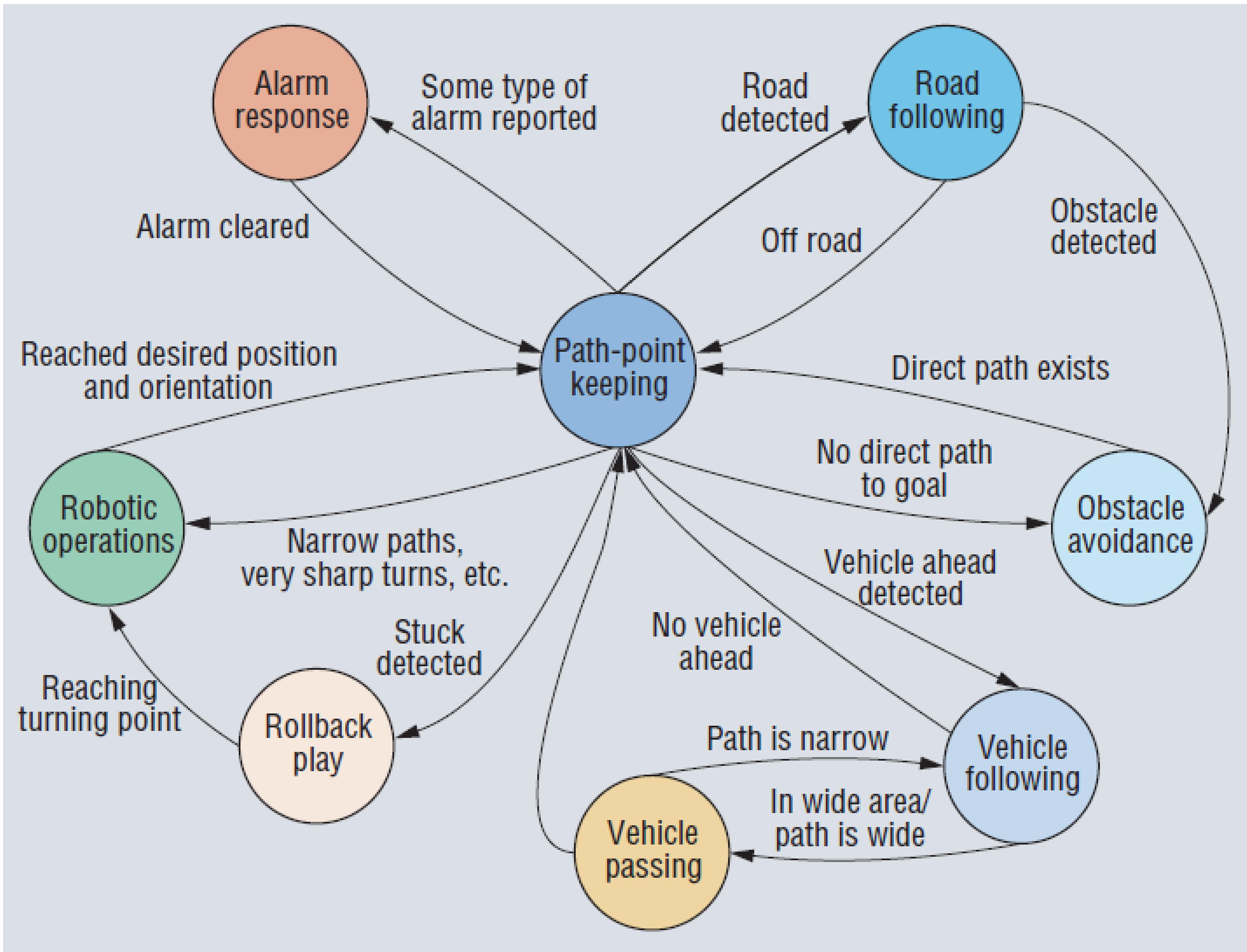
Hardware Overview



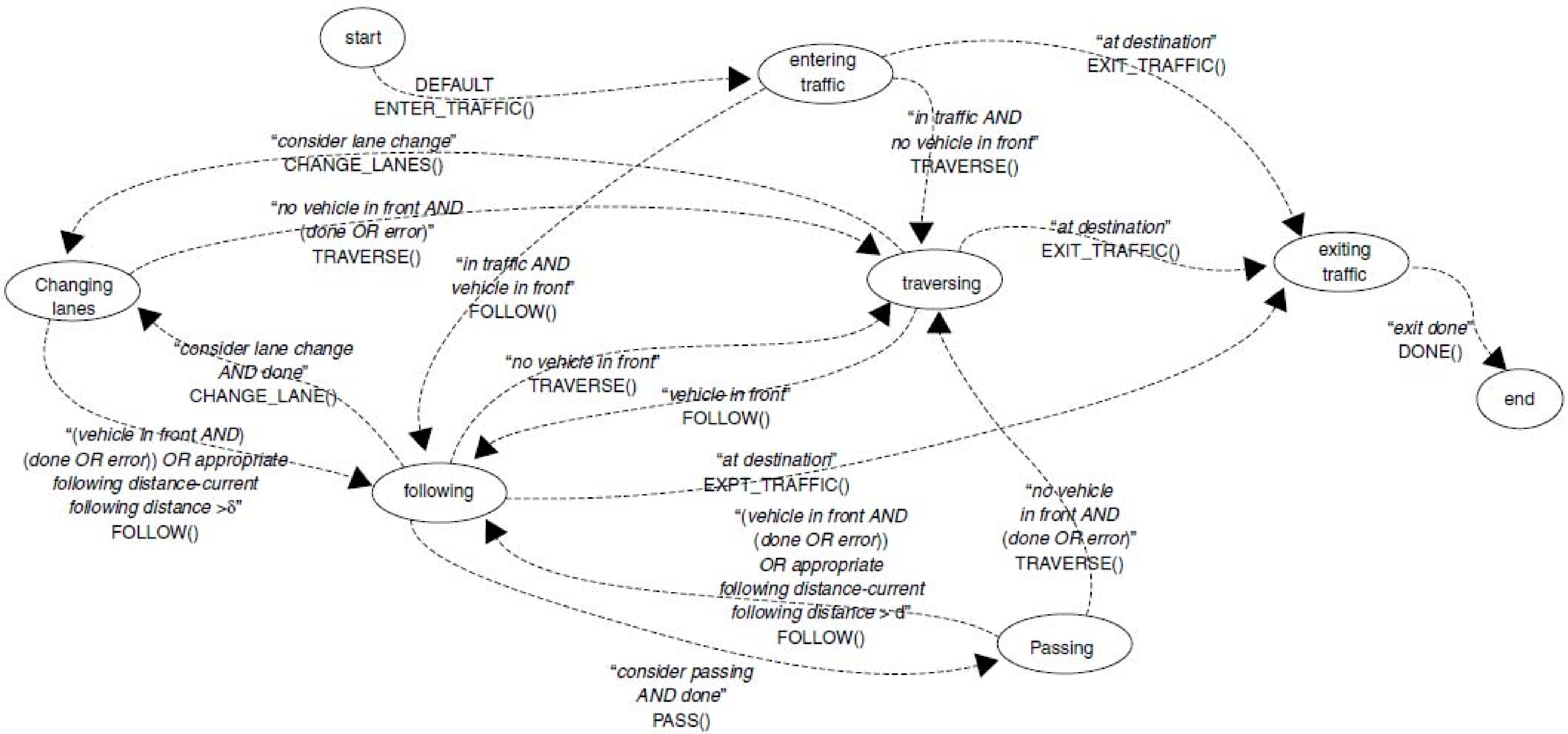
Data Communication



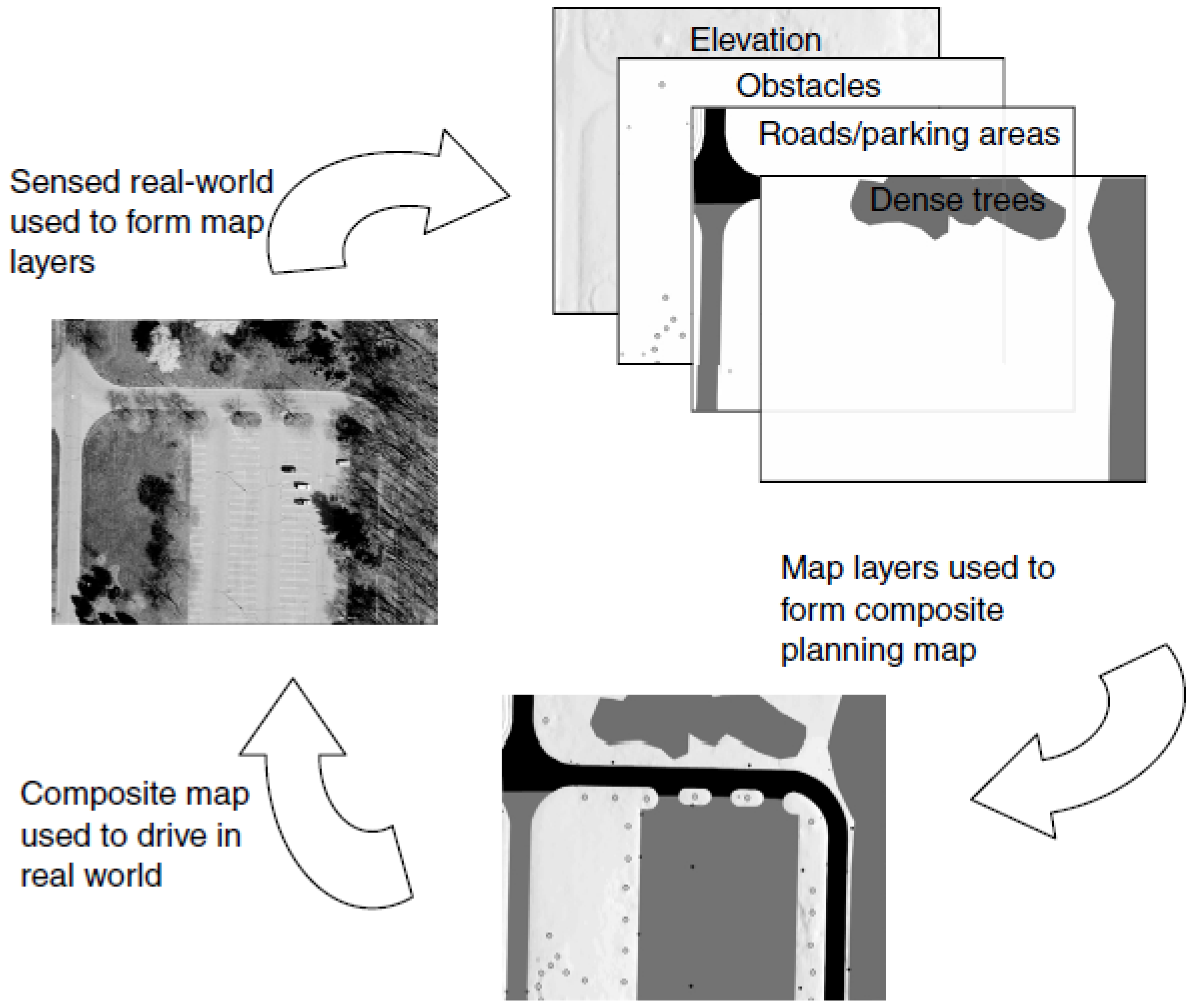
Finite-State Machine Diagram



Decision Making



Decision Making



ODOMETRY SENSORS FOR ROBOTS

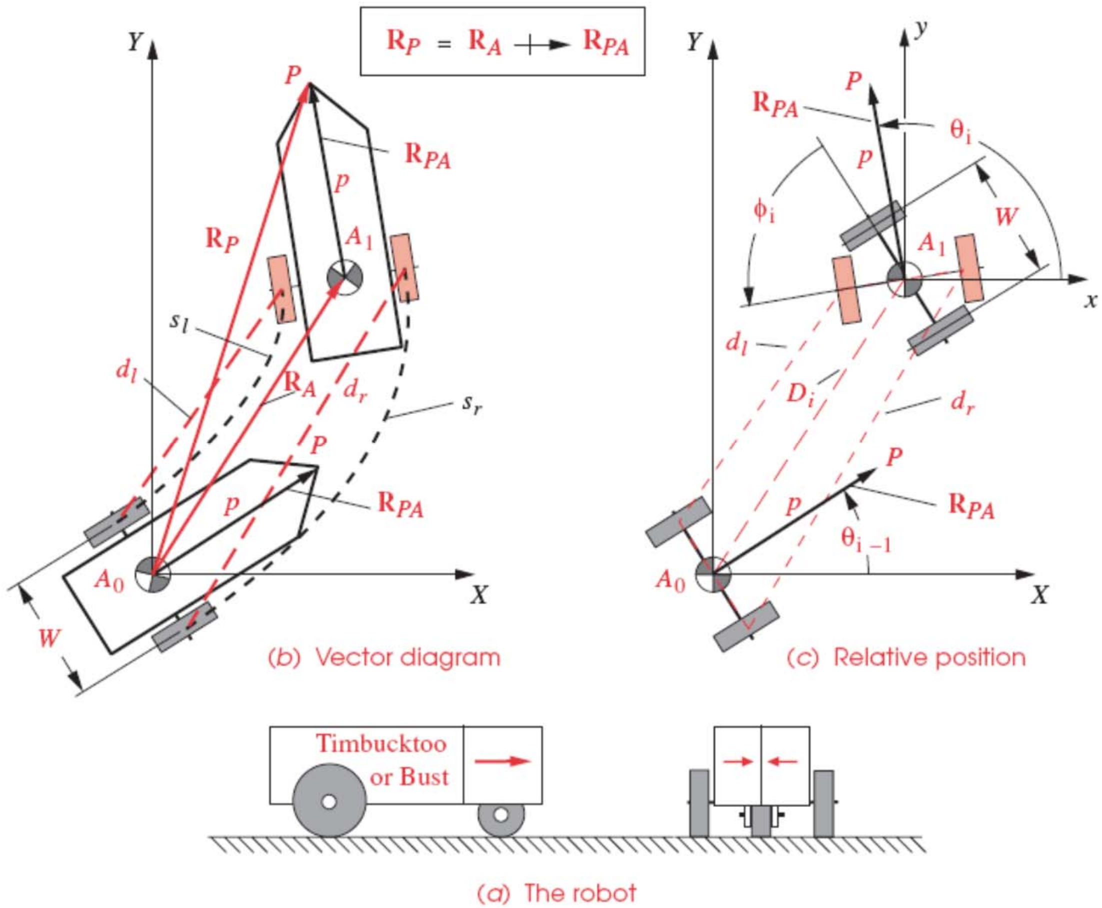
Terminology

- ✓ Mobile Robot Positioning
  - Relative Positioning (a.k.a dead reckoning)
  - Absolute Positioning (compass, GPS)

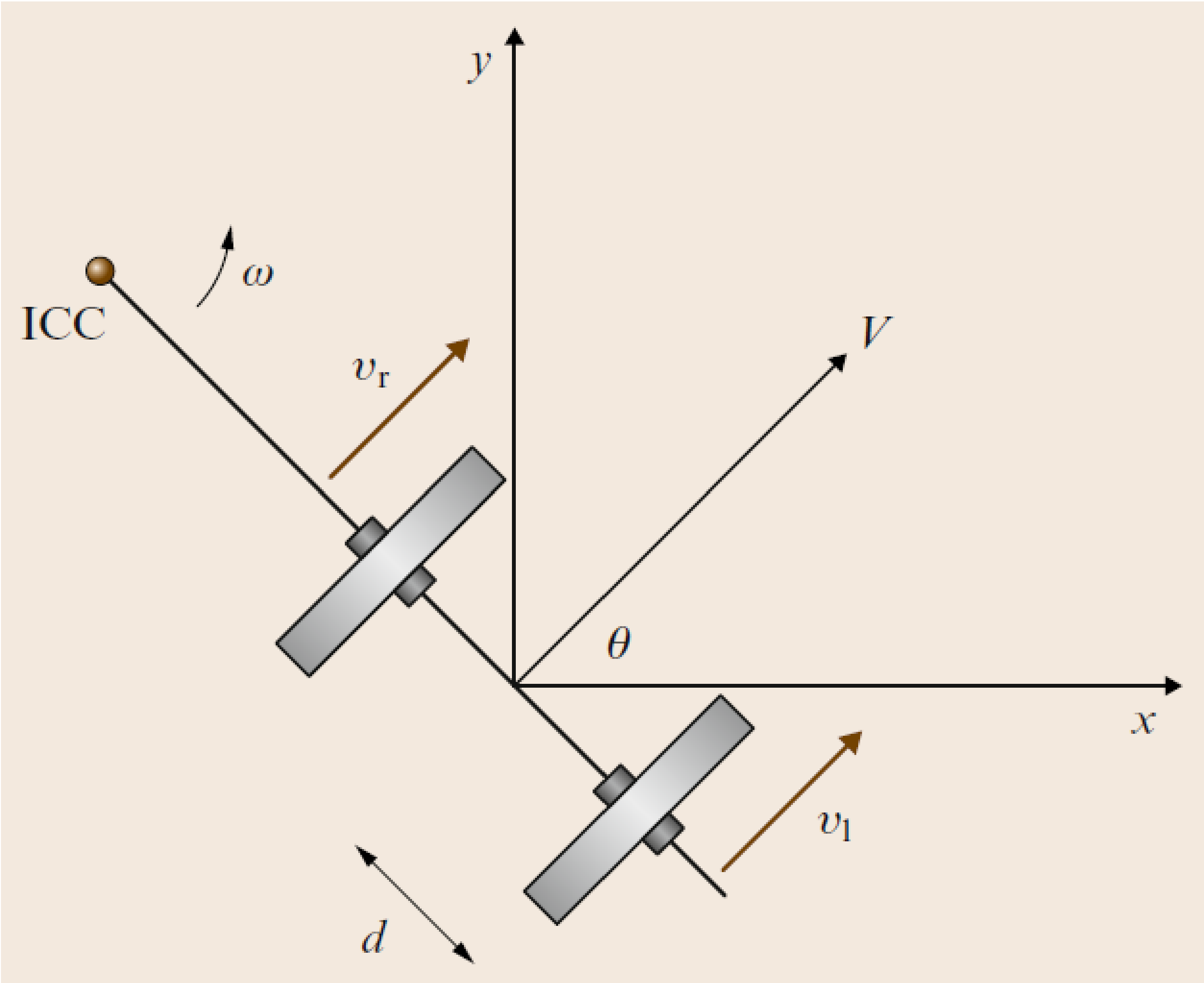
Terminology

- ✓ Dead reckoning
  - A mathematical procedure for determining the present location of a robot by advancing some previous position through known course and velocity information over a given length of time
- ✓ Odometry
  - Robot displacement along the path of travel directly derived from some onboard odometer

Dead Reckoning



Differential Drive Kinematics



Odometry

- ✓ Good short-term accuracy
- ✓ Inexpensive
- ✓ High sampling rates

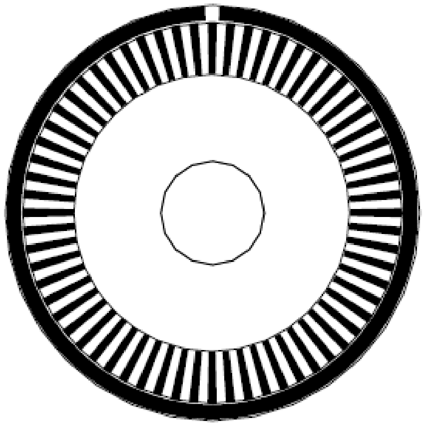
- ✓ Incremental motion information over time
- ✓ Unbounded accumulation of errors
  - ◆ Systematic
    - Kinematic imperfections of the robot
  - ◆ Non-systematic
    - Caused by the interaction of the ground surface with the wheels

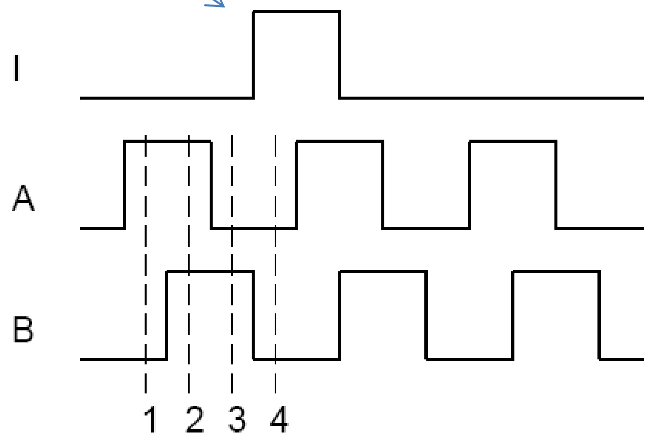
Odometry Sensors

- ✓ Potentiometers
  - Simple pots for applications not involving continuous rotation (get ~ 270° of rotation)
  - More sophisticated ‘pots’ (such as the analog version of the US Digital MA-3 magnetic shaft encoder) have continuous rotation
- ✓ Optical encoders
  - Incremental vs. absolute

Incremental Encoders

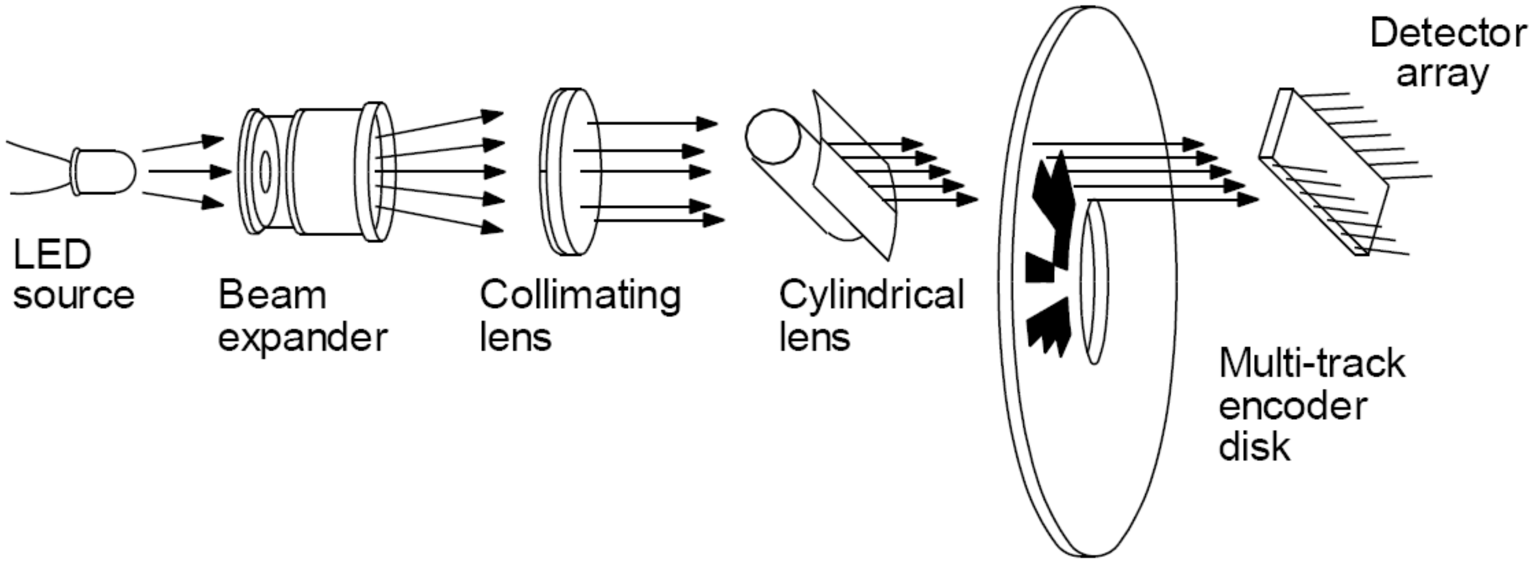
Incremental encoders may or
may not have an index channel

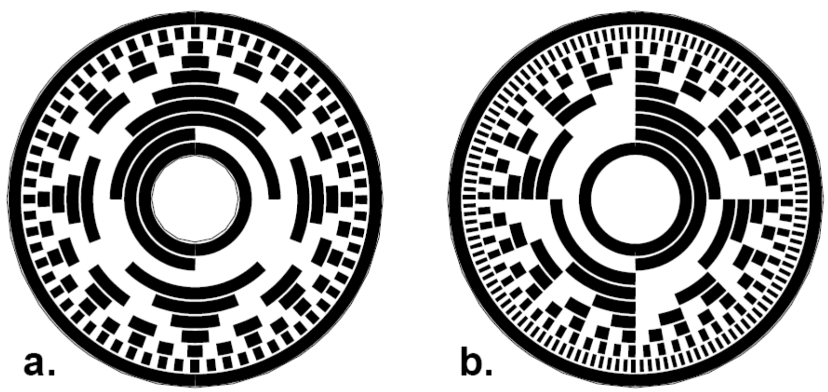




State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

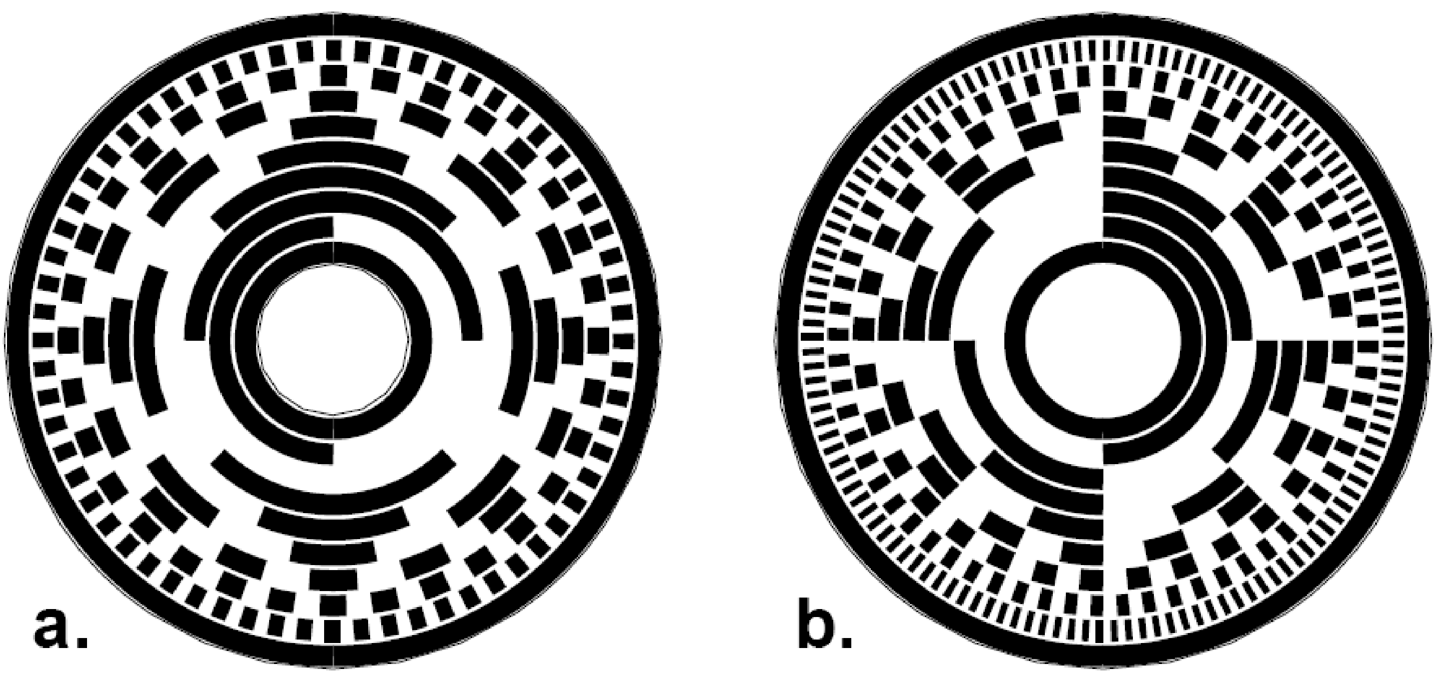
Absolute Encoders





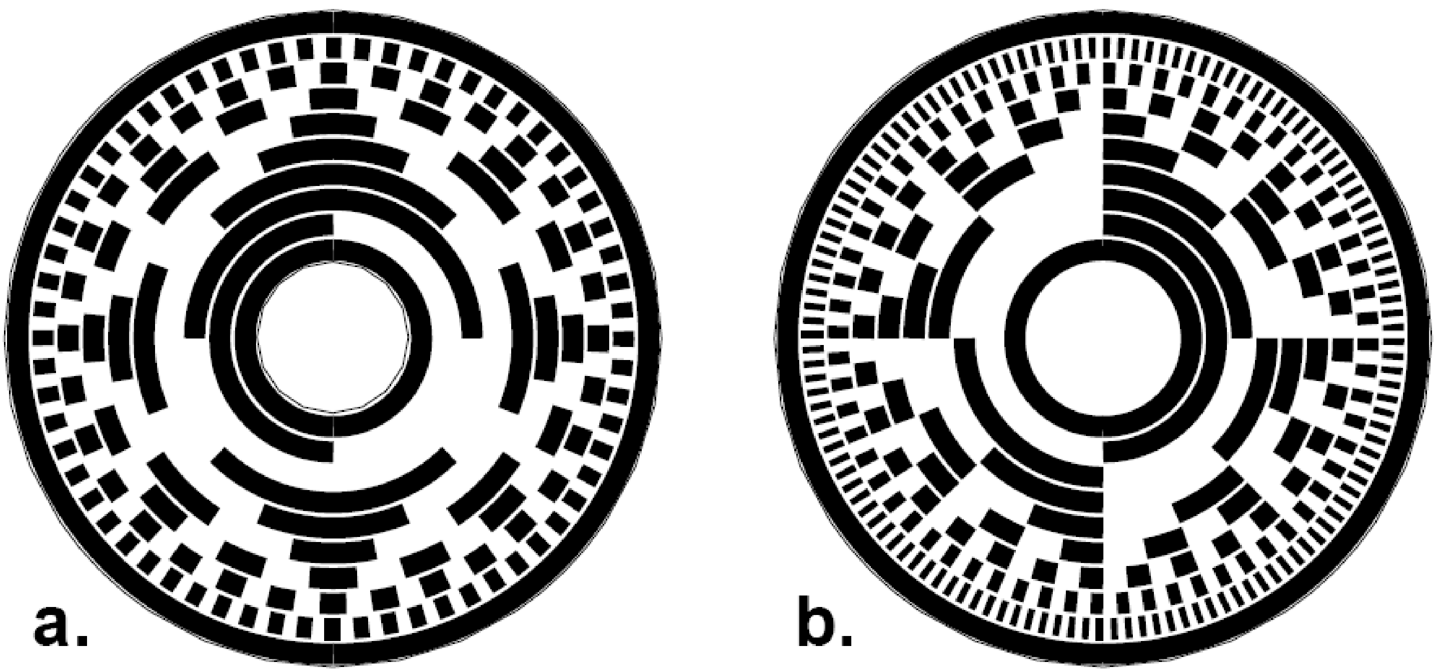
Gray Code vs. Binary Code

- ✓ The figures show an eight-bit Gray Code pattern on the left and a regular binary code pattern on the right



Gray Code vs. Binary Code

- ✓ The binary code has transitions where multiple bits are changing at the same time
- ✓ Example: 3 (0x00000011) → 4 (0b00000100)



a. b.

Gray Code vs. Binary Code

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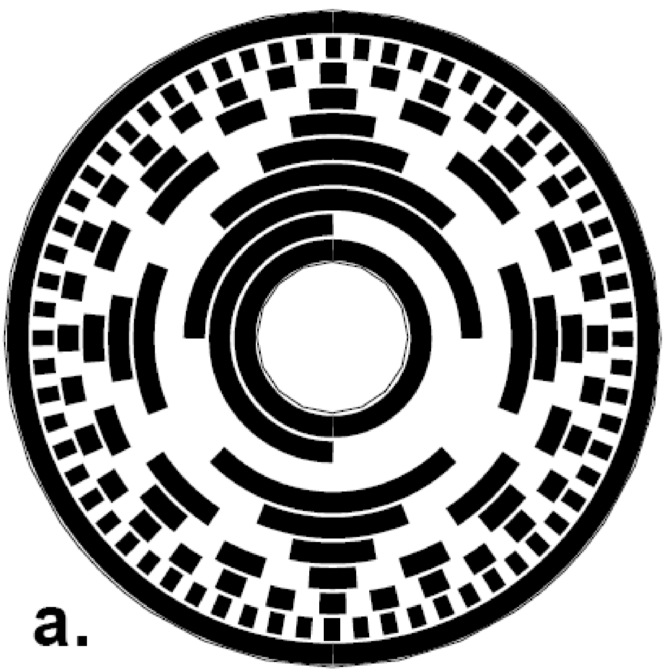


a.

Dec	Gray	Binary
0	000	000
1	001	001
2	011	010
3	010	011
4	110	100
5	111	101
6	101	110
7	100	111

Odometry Sensors

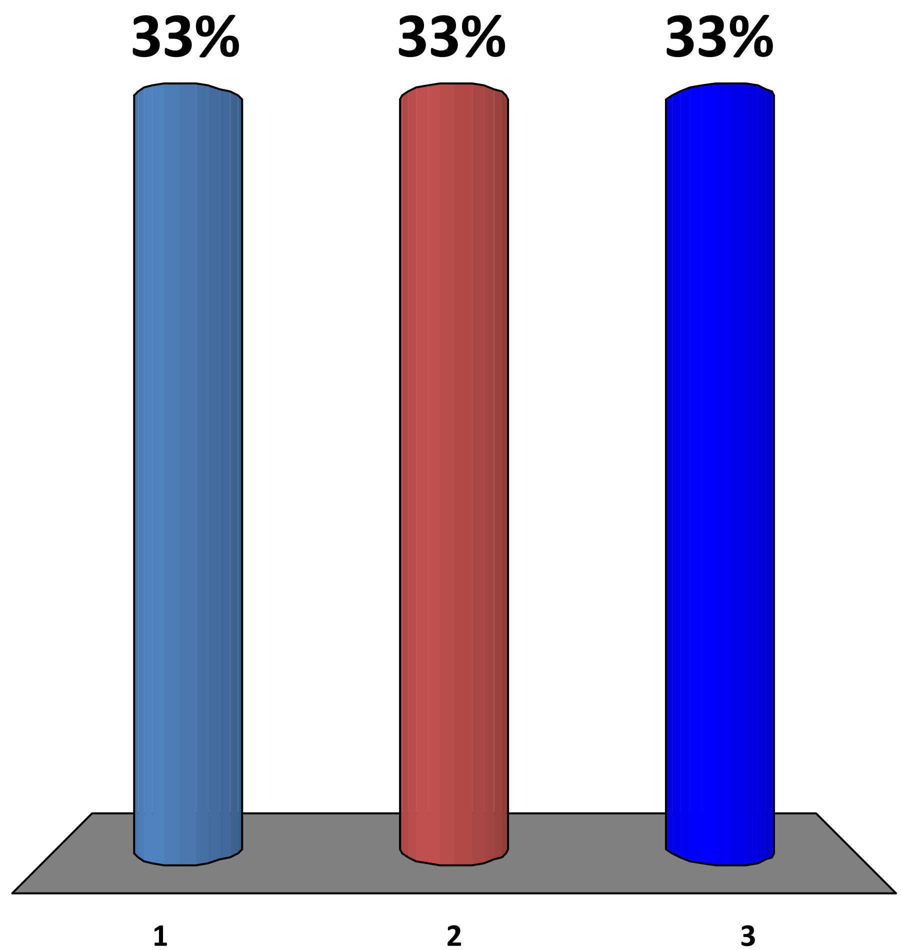
- ✓ Potentiometers
  - For applications not involving continuous rotation
- ✓ Optical encoders
  - Incremental vs. absolute
- ✓ Other solutions…

Odometry Sensors

- ✓ What happens if you are using an optical encoder on a drive wheel – and the wheel spins?

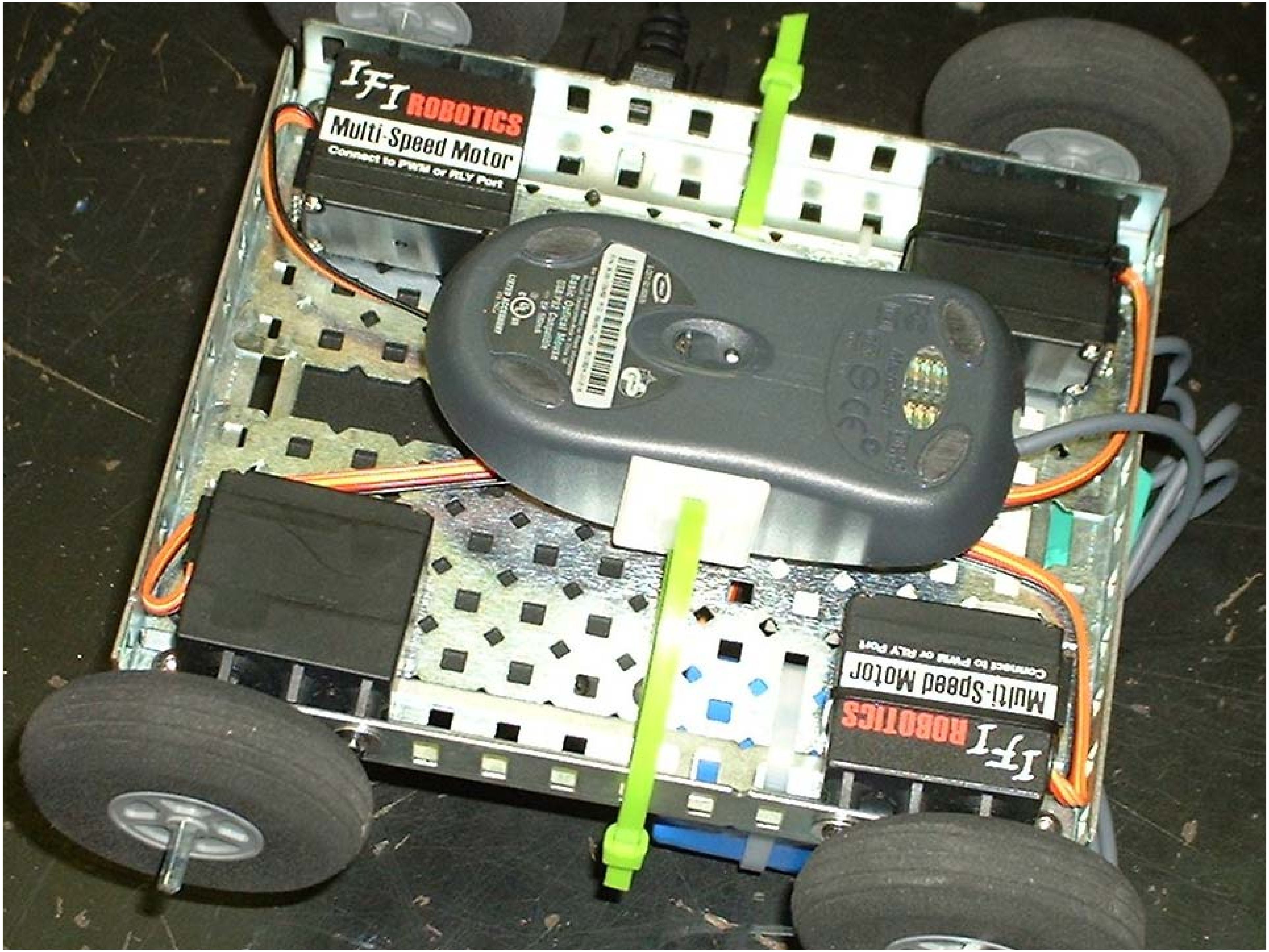
What happens if the wheel spins?

1. Nothing – if you just throw out the bad data
2. The robot gets lost
3. No idea…



Odometry Sensors

- ✓ What happens if you are using an optical encoder on a drive wheel – and the wheel spins?
- ✓ You need a way to detect movement that is insensitive to wheel slippage
- ✓ An optical mouse detects movement of the mouse relative to the surface below

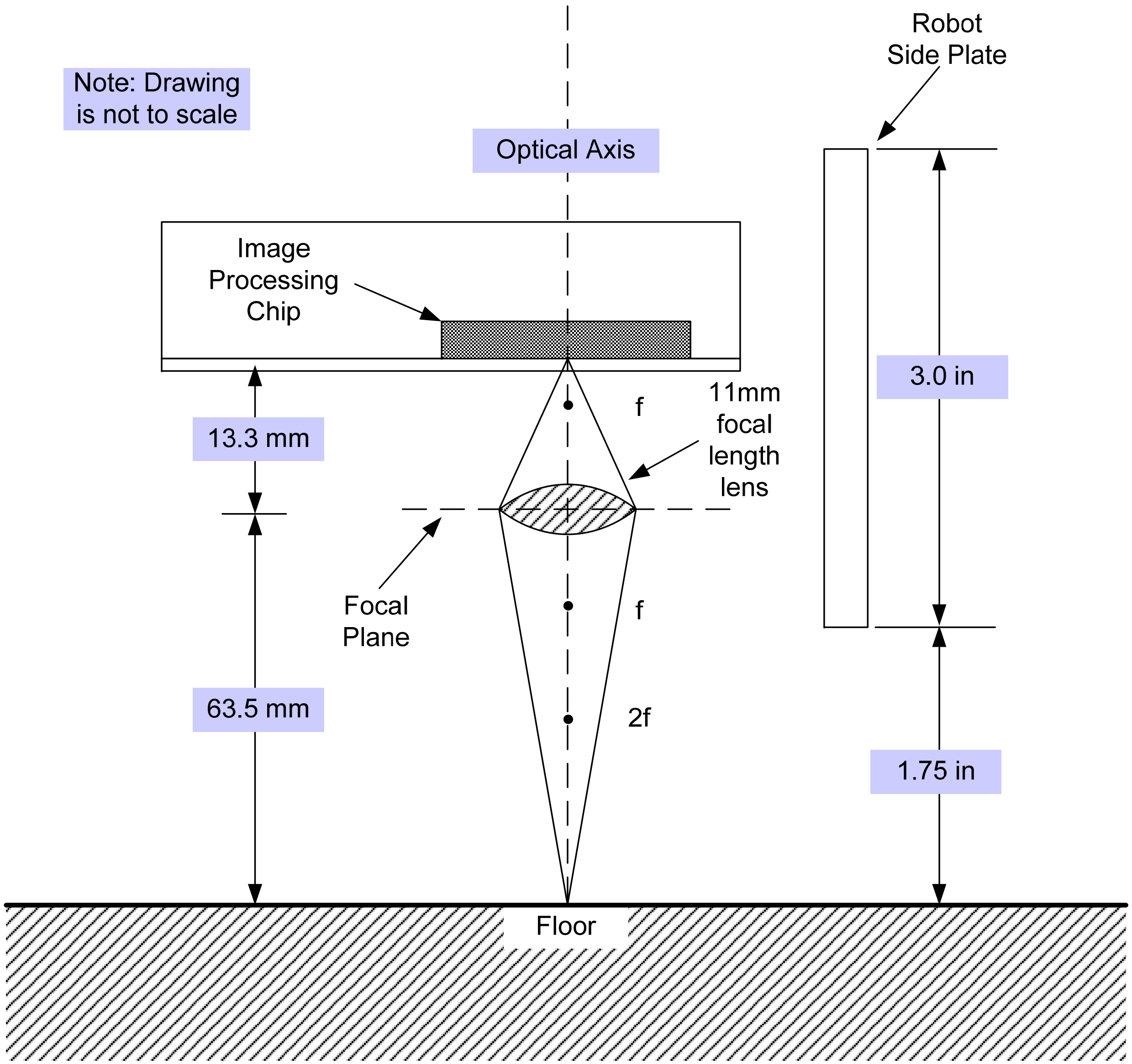

IFI ROBOTICS
Multi-Speed Motor
Connect to PWM or RLY Port

Odometry Sensors

- ✓ Problem: Putting an optical mouse on the floor below a robot has many drawbacks…
- ✓ Solution: OK – so get it up off the floor

- ✓ Problem: The mouse can no longer see the floor
- ✓ Solution: Give the mouse glasses!

Odometry Sensors



Odometry Sensors

- ✓ Theoretical accuracy of ±0.25 inch over a 27 x 54 foot playing field
- ✓ Could handle robot speeds of up to 10 m/s (≈ 22 mph)
- ✓ Not bad for < $20 and a little work…

SONAR SENSING

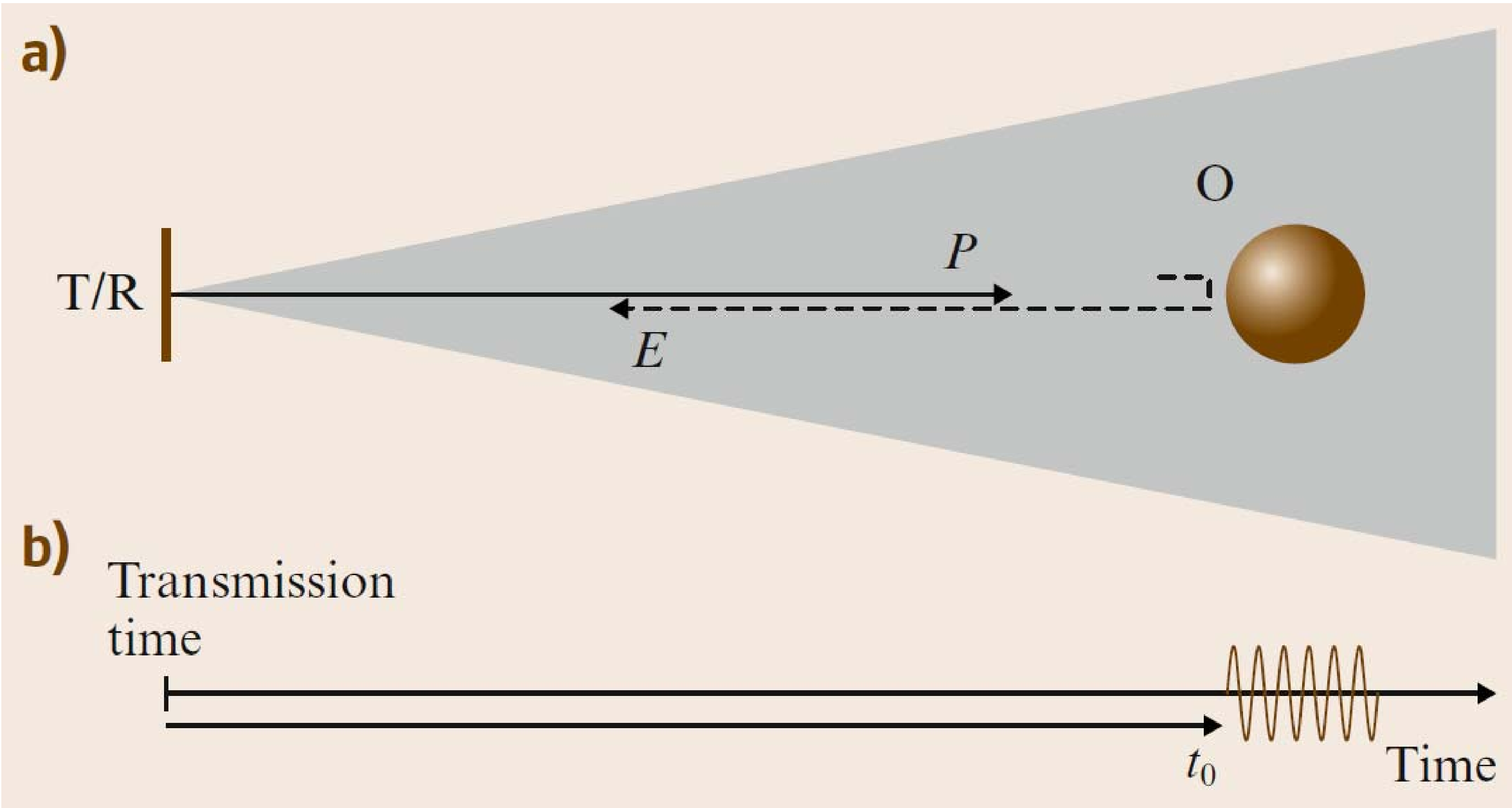
Sonar in Robotics

- ✓ Obstacle avoidance
- ✓ Sonar mapping
- ✓ Object recognition

Sonar Sensing

- ✓ Employs acoustic pulses and their echoes to measure the range to an object
- ✓ The object range is proportional to the echo travel time
- ✓ Low cost, light weight, low power consumption, and low computational effort
- ✓ In some applications, such as in underwater and low-visibility environments, sonar is often the only viable solution

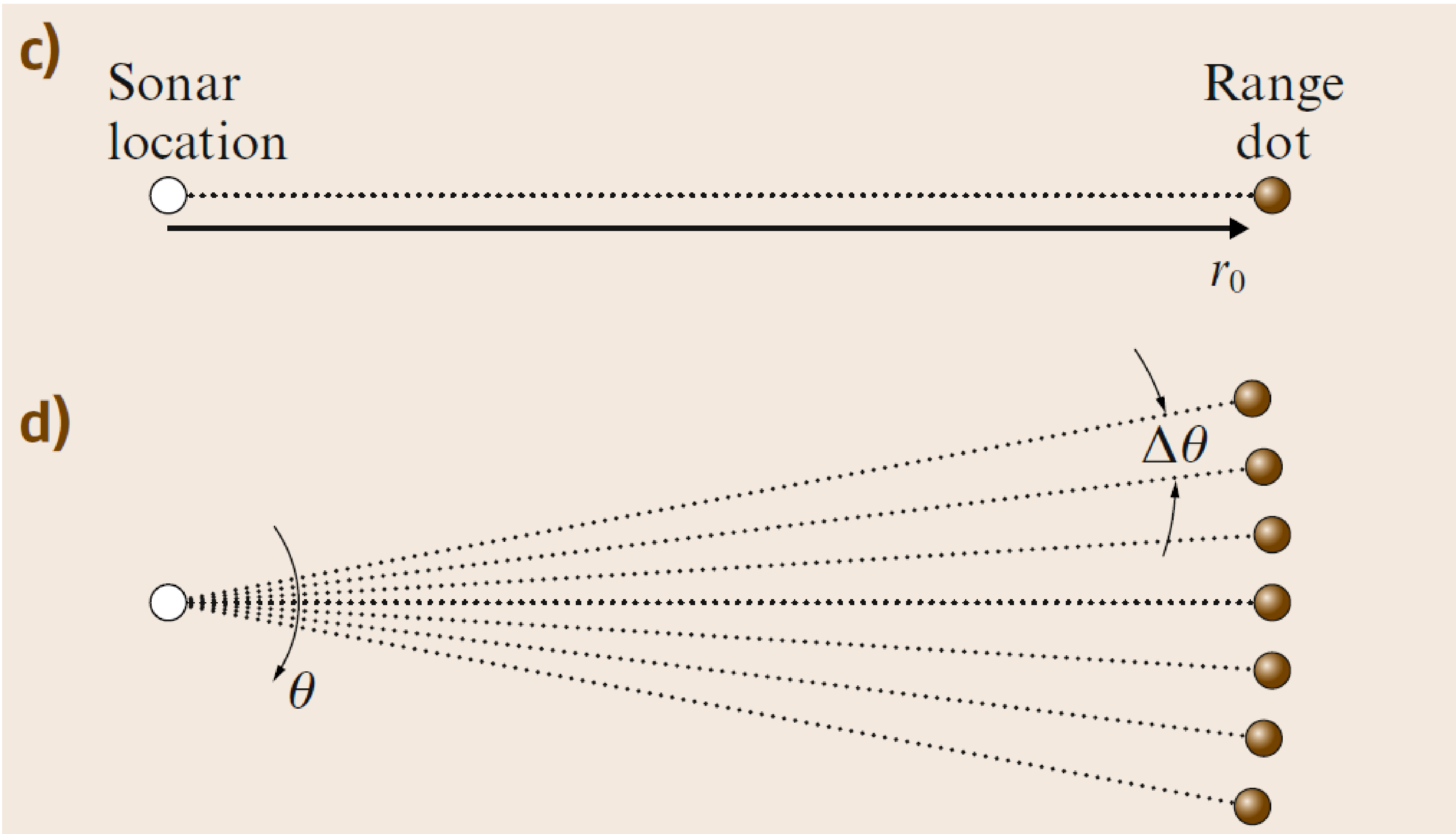
Sonar Ranging Principles



Limitations of Sonar

- ✓ The wide sonar beam causes poor directional resolution

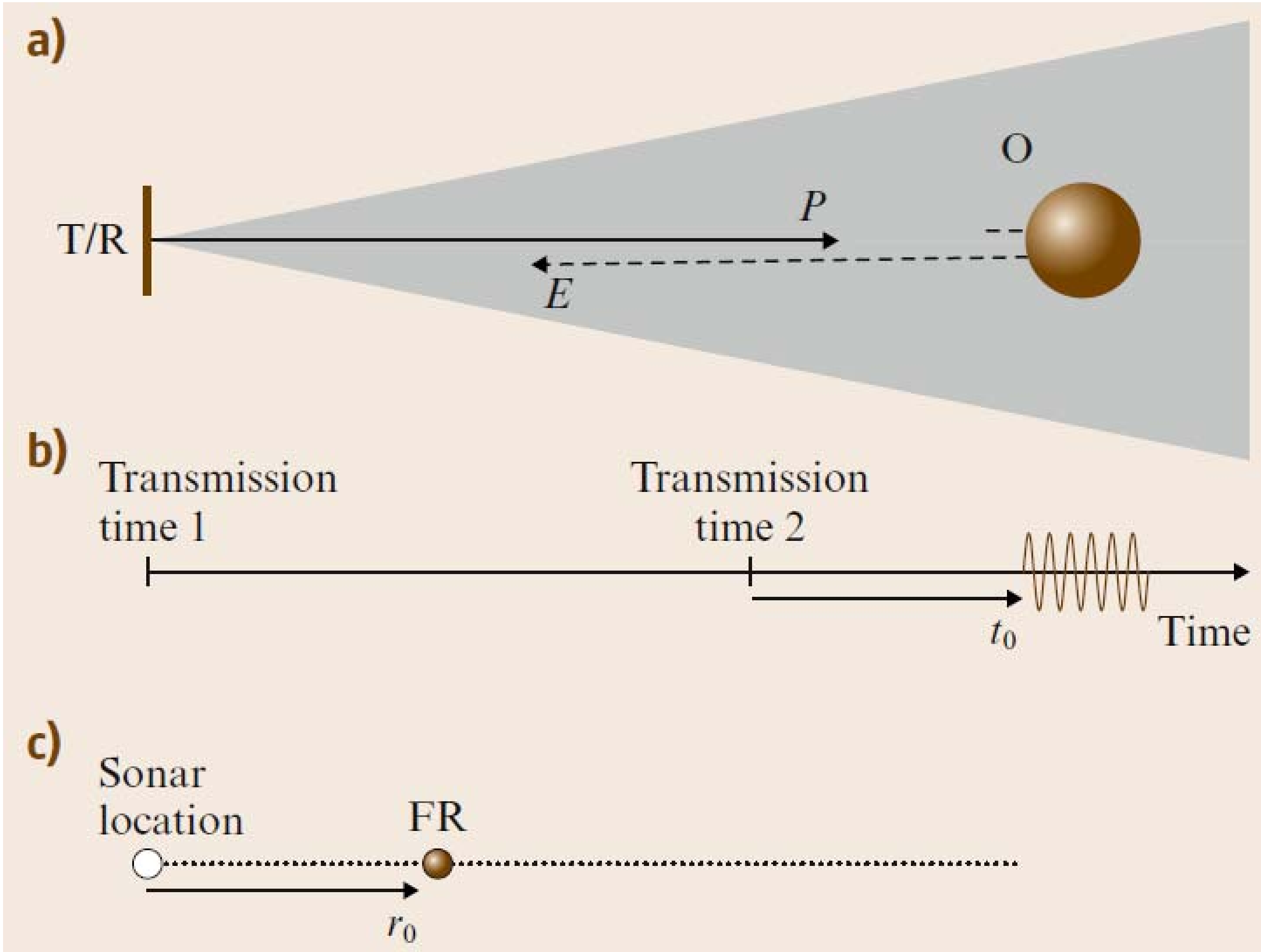
Sonar Ranging Principles



Limitations of Sonar

- ✓ The wide sonar beam causes poor directional resolution
- ✓ The slow sound speed, relative to an optical sensor, reduces the sonar sensing rate

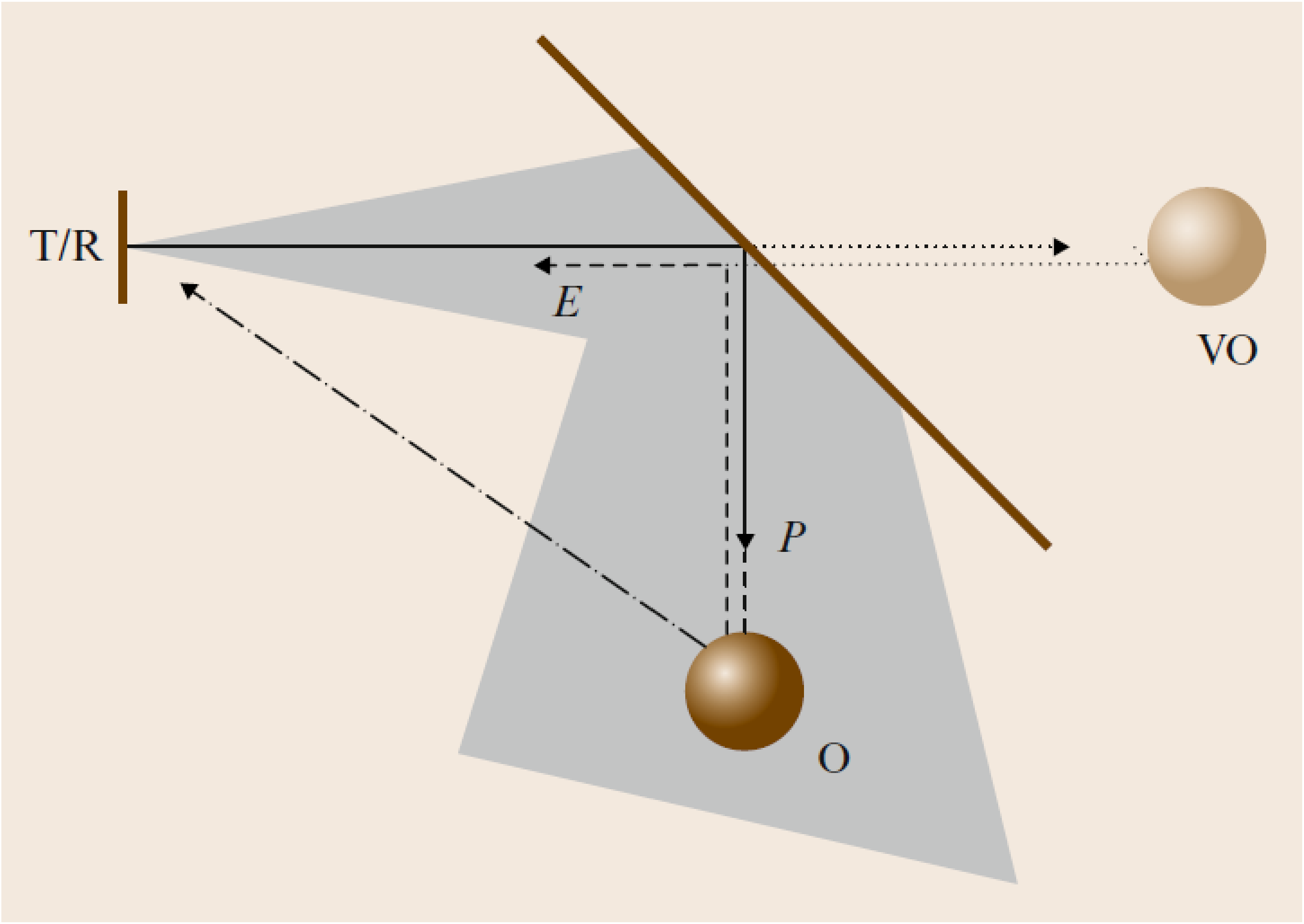
False Range Reading



Limitations of Sonar

- ✓ The wide sonar beam causes poor directional resolution
- ✓ The slow sound speed, relative to an optical sensor, reduces the sonar sensing rate
- ✓ Smooth surfaces at oblique incidence do not produce detectable echoes
- ✓ Artifacts caused by beam side-lobes and multiple reflections produce range readings in the environment where no objects exist

Sonar Limitations



Limitations of Sonar

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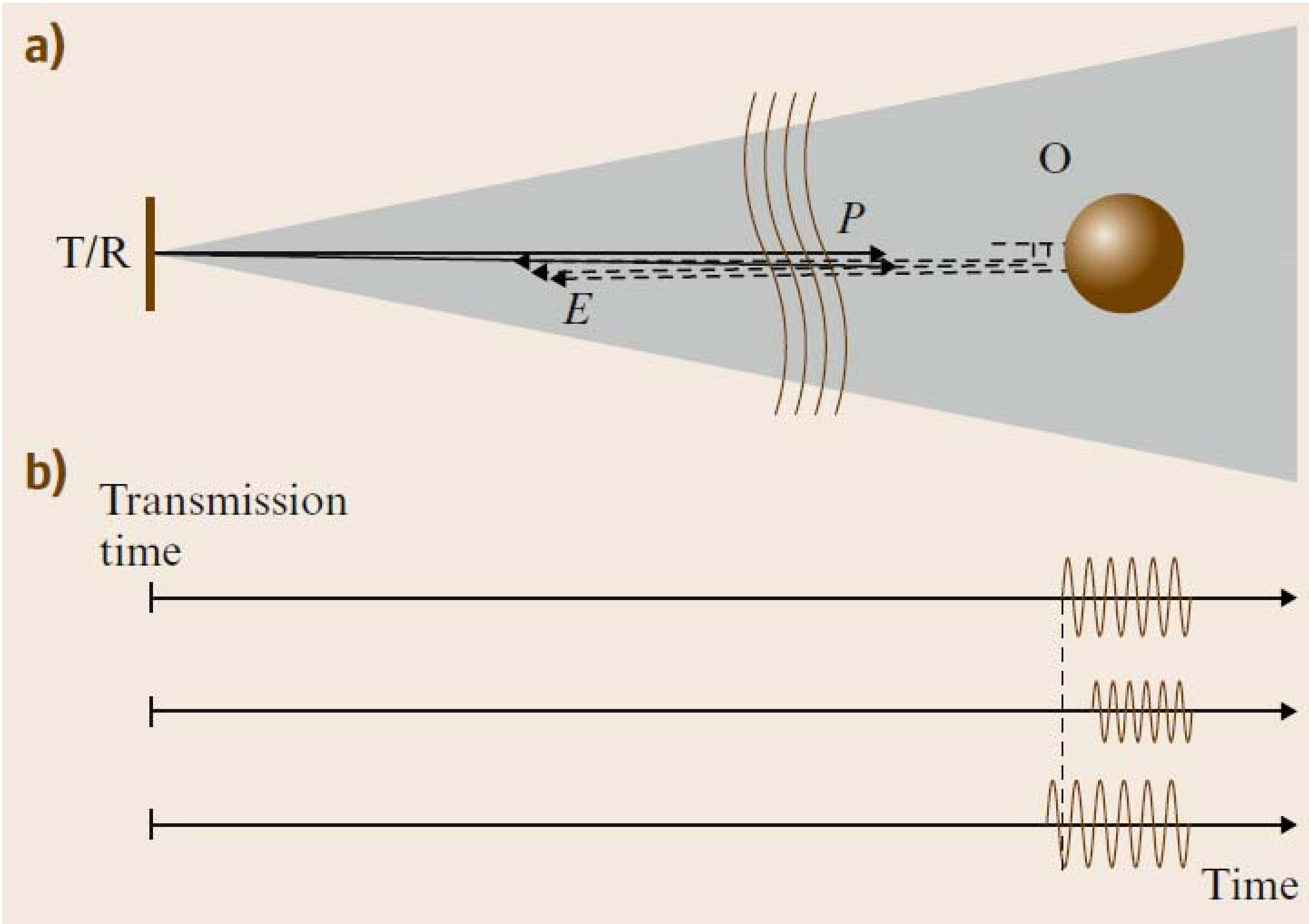
- ✓ Travel time and amplitude variations in the echoes caused by inhomogeneities in the sound speed

Sonar Limitations



LASER BASED RANGE SENSORS

Laser-Based Range Sensors

- ✓ Triangulation sensors
- ✓ Phase-modulation sensors
- ✓ Time-of-flight sensors

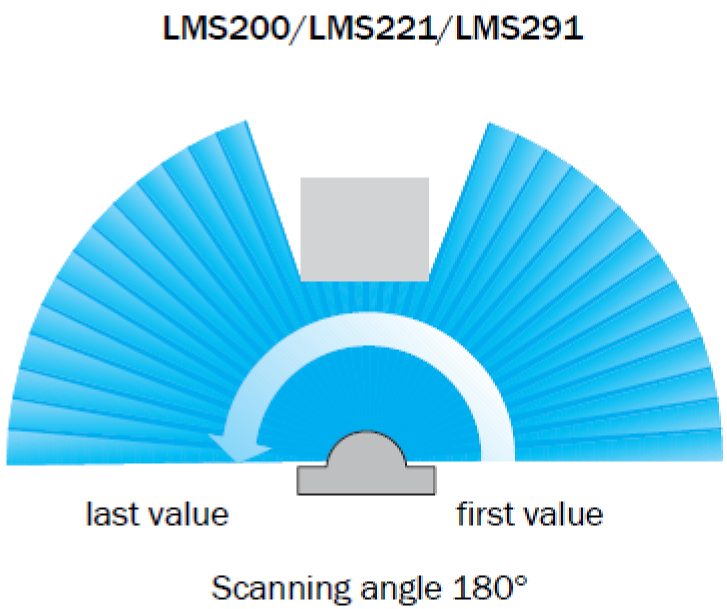
SICK LMS291

Features and Advantages

- Non-contact optical measurement, even over longer distances
- Rapid scanning times, thus measurement objects can be move at high speed
- No special target-object reflective properties necessary
- No reflectors and no marking of the measurement objects necessary
- Backgrounds and surroundings do not have any influence on the measurements
- Measurement objects may be in any position
- Measurement data is available in real-time and can be used for further processing or control tasks
- Active system – no illumination of the measurement area required
- Simple mounting and commissioning
- Completely wheaterproof variante (IP 67)

Fig. 2-1: Type overview: Housing designs of the LMS2xx

Scanning Angle



Overview of LMS2xx

Type	Scanning angle	Angular resolution	Resolution/ typical Measurement Accuracy	Typical Range[1]	Temperature Range	Heating	Fog Correction
LMS200-30106[2]	180°	0.25°; 0.5°; 1°	10 mm/±15 mm	10 m	0 to +50 °C	Accessory[8]	no
LMS209-S02[2][3]	180°	0.25°; 0.5°; 1°	10 mm/±15 mm	10 m	0 to +50 °C	Accessory[8]	no
LMS211-30206	100°	0.25°; 0.5°; 1°	10 mm/±35 mm	30 m	–30 to +50 °C	yes[9]	yes
LMS211-30106	100°	0.25°; 0.5°; 1°	10 mm/±15 mm	10 m	–30 to +50 °C	yes[9]	no
LMS221-30206[2]	180°	0.25°; 0.5°; 1°	10 mm/±35 mm	30 m	–30 to +50 °C	yes	yes
LMS221-30106[2]	180°	0.25°; 0.5°; 1°	10 mm/±15 mm	10 m	–30 to +50 °C	yes	no
LMS291-S05[2]	180°	0.25°; 0.5°; 1°	10 mm/±35 mm	30 m	0 to +50 °C	Accessory[8]	yes
LMS291-S14[4]	90°	0.5°	10 mm/±35 mm	30 m	0 to +50 °C	Accessory[8]	yes
LMS291-S15[2][6]	180°	0.25°; 0.5°; 1°	10 mm/±35 mm	30 m	0 to +50 °C	Accessory[8]	yes

LMS2xx

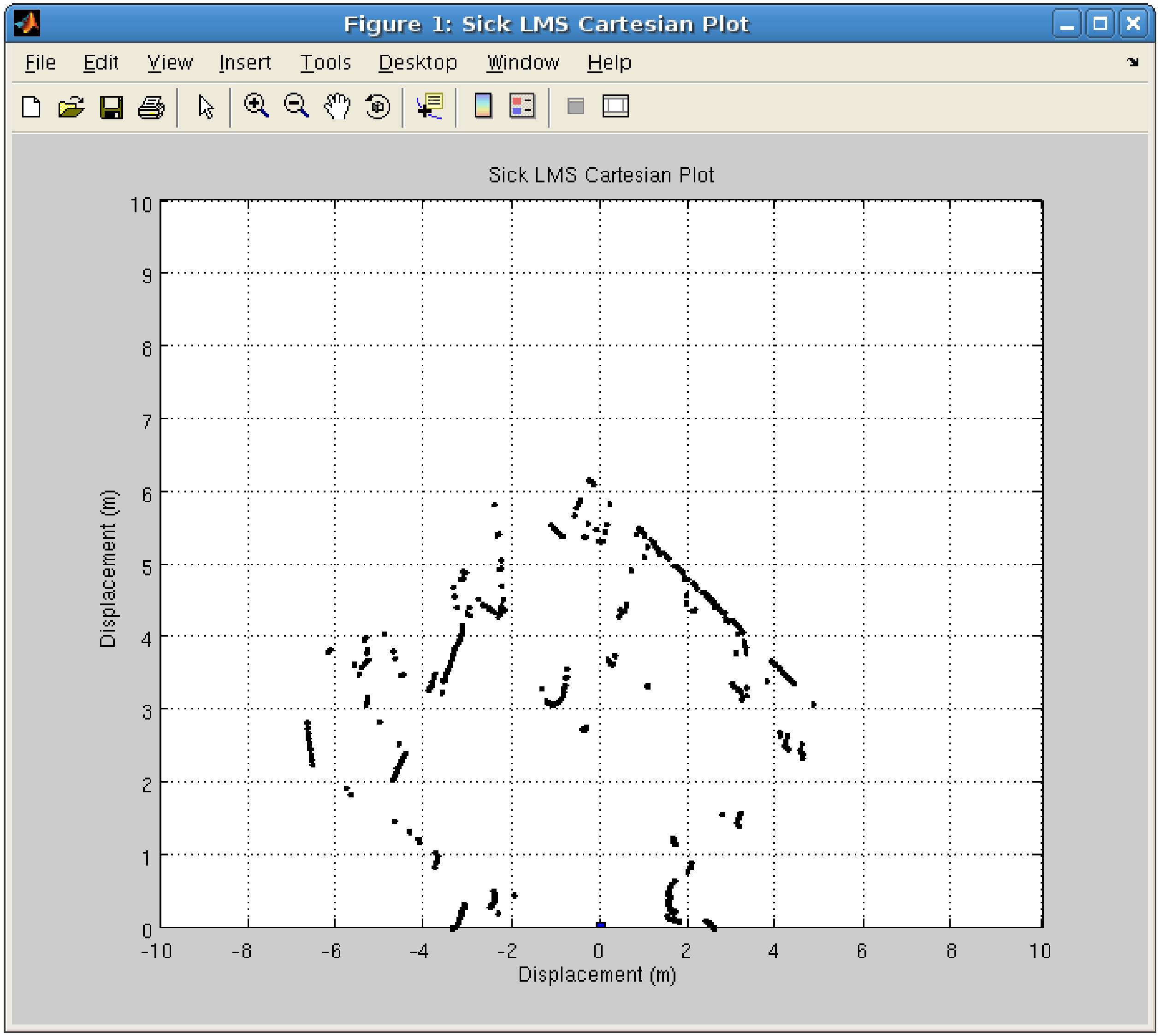
12 Technical Data

Type	**Indoor: LMS200, Outdoor: LMS211, LMS221, LMS291**
Scanning angle (field of vision)	100°/180° (type-dependent, see *Table 11-1, Page 27*)
Motor speed	75 Hz
Angular resolution (response time)	0.25°[1)] (53.33 ms); 0.5° (26.66 ms); 1° (13.33 ms); selectable
Range	Max. 80 m (type-dependent, see *Table 11-2, Page 27*)
Measurement resolution	10 mm
Measurement accuracy	typical ±35 mm (LMS200-30106, LMS211/LMS221-30106: typical ±15 mm)
Systematic error[2)]	LMS200-30106/LMS211-30106/LMS221-30106: – mm-mode: typical ±15 mm at range 1 to 8 m – cm-mode: typical ±4 cm at range 1 to 20 m LMS211/LMS211-30206/LMS291/LMS221-30106/LMS2x1-Sxx: – mm-mode: typical ±35 mm at range 1 to 20 m – cm-mode: typical ±5 cm at range 1 to 20 m

LMS2xx

Statistical error[3]	LMS200-30106/LMS211-30106/LMS221-30106: mm-mode: typical 5 mm at range ≤ 8 m/ reflectivity ≥ 10 %/ light ≤ 5 klx LMS211/LMS211-30206/LMS291/LMS221-30106/LMS2x1-Sxx: mm-mode: typical 10 mm at range 1 to 20 m/ reflectivity ≥ 10 %/ light ≤ 5 klx
Laser diode (wavelength)	Infra-red (λ = 905 nm)
MTBF of LMS2xx[4]	Indoor devices: 70,000 h Outdoor devices: 50,000 h
Laser class of device	Class 1 (eye-safe), to EN/IEC 60825-1 and to 21CFR 1040.10
Optical indicators	3 x LED (LMS200/LMS291 only)
Data interface	RS 232 or RS 422 (selectable in the connector plug)
Data transfer rate	RS 232: 9.6 / 19.2 kbd RS 422: 9.6 / 19.2/ 38.4/ 500 kbd
Data format	1 start bit, 8 data bits, 1 stop bit, no parity (fixed)
Switching inputs	All LMS2xx except LMS2xx-S14 (LMS Fast): 1 x (“Restart“ or “Field set switching“), U_{in} = 12 to 24 V, I_{in} = 5 mA
Switching outputs (standard device)	LMS200/LMS291/LMS211/LMS221: 3 x PNP (OUT A to OUT C), high, typical 24 V DC (“field OK“), short-circuit-proof, selectable restart delay after field infringement (0; 100 ms to 255 s) – OUT A, OUT B (each max. 250 mA): “field infringement“ – OUT C (max. 100 mA): “field infringement/error indication (Weak)[5]“

Matlab Toolbox



Hokuyo URG-04LX-UG01

- ✓ This lidar is used in RBE 3002
- ✓ Much smaller (50mm x 50mm x 70mm)
- ✓ Much lighter: 160g
- ✓ Much lower power: 2.5W (runs off USB!)
- ✓ Lower max range: 5.6m x 240°
- ✓ Much lower cost: ~$1300

GPS

Autonomous Vehicles

- ✓ Unmanned Ground Vehicles (UGVs)
  - Off-road navigation and terrain mapping
- ✓ Intelligent Transport Systems (ITSs)
  - Safer and efficient transport in structured or urban settings

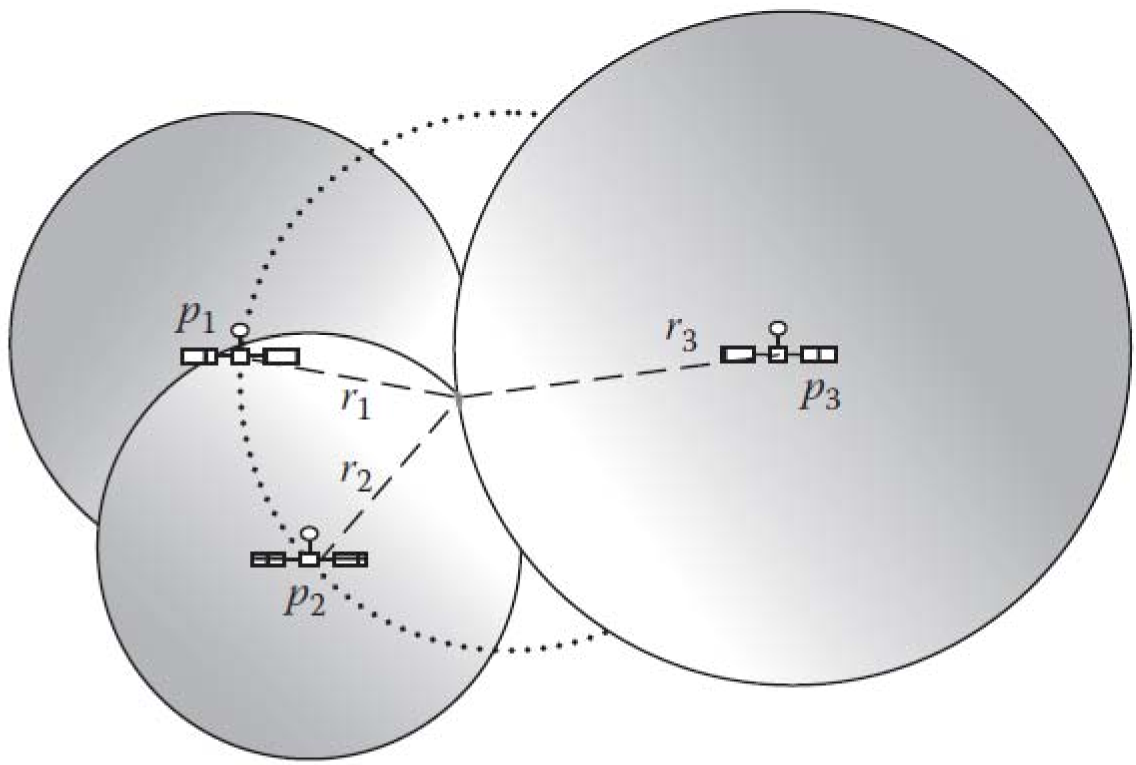
Sensors for Autonomous Vehicles

- ✓ INS – Inertial Navigation System /
  IMU – Inertial Measurement System
  - IMU provides high sample rate measurements of the vehicle accelerations and angular rotation rates
  - Integrates the IMU measurements to produce position, velocity, and attitude estimates
- ✓ GPS receiver
  - Estimates the position and velocity of the receiver antenna
- ✓ LIDAR
- ✓ Vision

GNSS

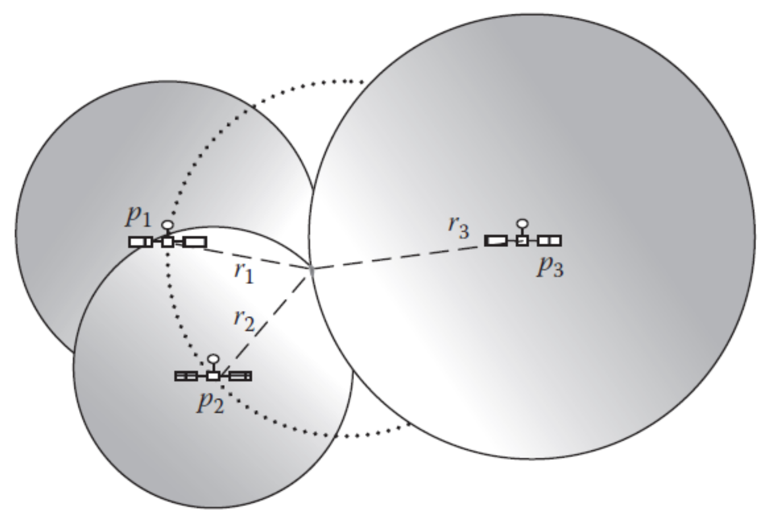
- ✓ Global Navigation Satellite System
  - NAVSTAR GPS – USA
  - GALLILEO – EU
  - GLONASS – Russia
  - COMPASS – China

GPS: Basic Idea



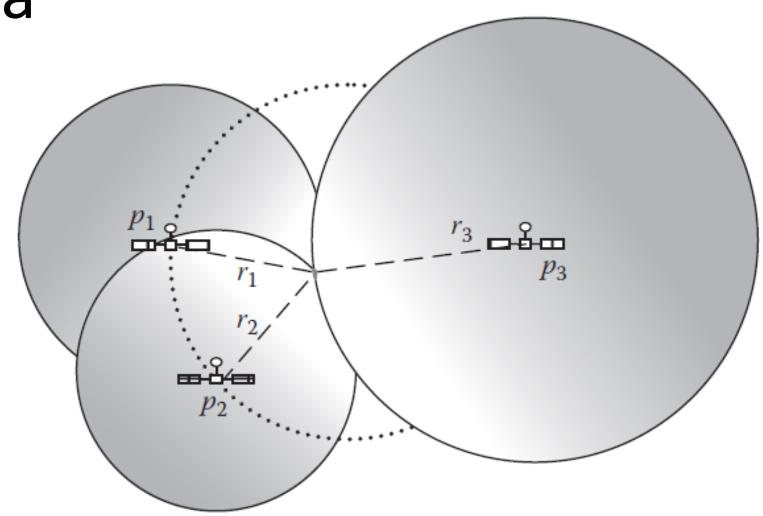
GPS: Basic Idea

- ✓ Each GPS satellite continuously transmits a microwave radio signal composed of two carriers, two codes, and a navigation message
- ✓ When a GPS receiver is switched on, it will pick up the GPS signal through the receiver antenna
- ✓ Once the receiver acquires the GPS signal, it is processed

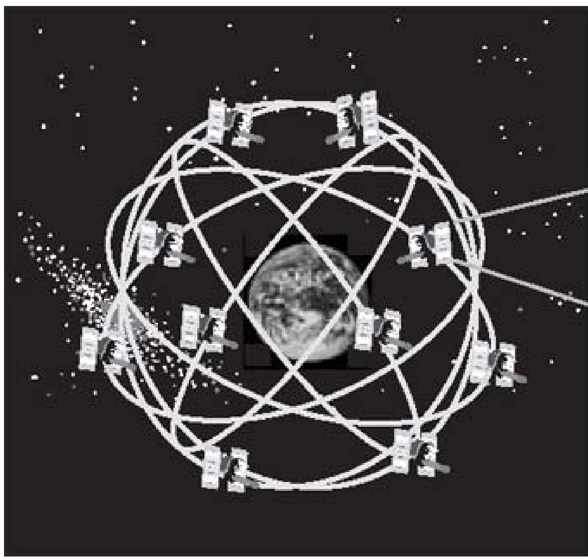


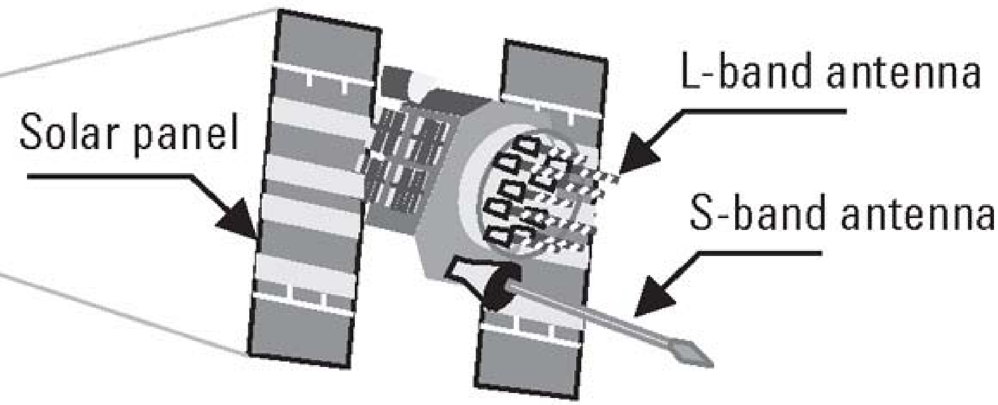
GPS: Basic Idea

- ✓ The partial outcome of the signal processing consists of the distances to the GPS satellites through the digital codes (known as the pseudoranges) and the satellite coordinates through the navigation message
- ✓ Theoretically, only three distances to three simultaneously tracked satellites are needed
- ✓ From a practical point of view, a fourth satellite is needed to account for the receiver clock offset

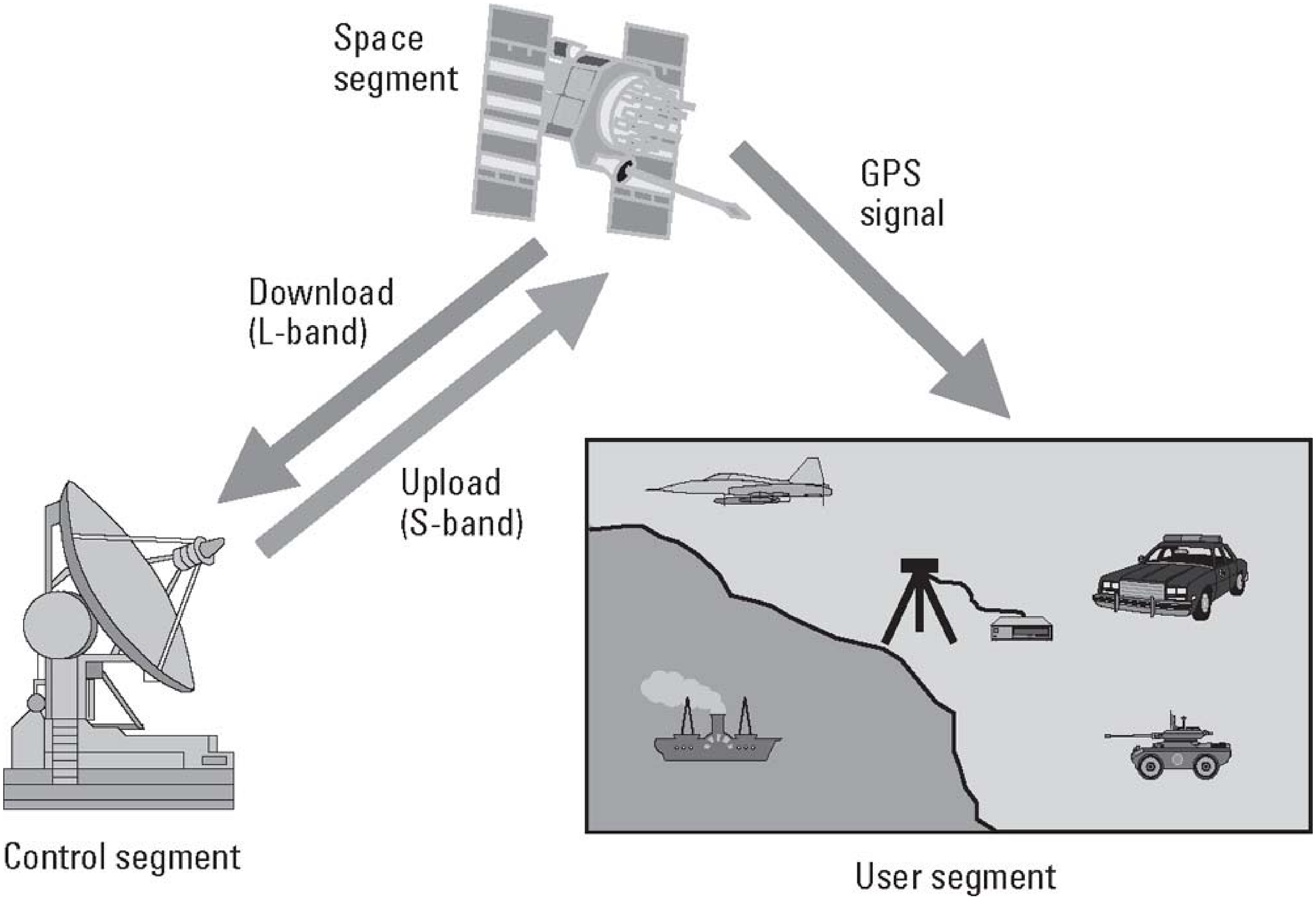


GPS





GPS


Space
segment
GPS
signal
Download
(L-band)
Upload
(S-band)
Control segment
User segment

GPS

- ✓ The space segment:
  - 24 satellites with well-known positions in six earth-centered orbital planes with four equally spaced satellites in each plane
  - GPS satellite signal:
    - Two sine waves, two digital codes and a navigation message
  - Signals are controlled by atomic clocks on board

GPS

✓ The control segment:

- A worldwide network of tracking stations
- Master control station (MCS) located in the United States
- Track the GPS satellites
  - To determine and predict satellite locations, system integrity, behavior of the satellite atomic clocks, atmospheric data, the satellite almanac, and other considerations
- Periodically uploads to the satellite its prediction of future satellite positions and satellite clock time corrections
  - Thank You Hendrick Lorentz and Albert Einstein! Without relativistic corrections, GPS would not be nearly as accurate as it is today!
  - See http://metaresearch.org/cosmology/gps-relativity.asp for a nice discussion of this

GPS

- ✓ The user segment:
  - All military and civilian users
  - Track the ranging signals of selected satellites and convert them into position, velocity, and time estimates used for navigation, positioning, time dissemination, etc.

GPS

- ✓ GPS utilizes the concept of one-way time-of-arrival (TOA) ranging to determine user position
- ✓ The *pseudorange* is measured in a GPS receiver by evaluating the GPS signal time delay from the satellite

GPS

- ✓ Designed to work outdoors
- ✓ The signal is extremely weak
  - The total radiated power from each satellite is just 27W
- ✓ The satellites are far away
  - more than 20,000-km high
- ✓ When the signal reaches the GPS receiver on the Earth, the received signal power is about 100 attowatts (100×10^{-18} W)

GPS

- ✓ The main drawback of GPS remains its high sensitivity to multipath and interference which are the two main sources of errors in range and position estimations
- ✓ GPS signals are in the microwave band:
  - They can pass through plastic and glass, but are absorbed by water (wood, heavy foliage) and are reflected by many materials

GPS Localization

- ✓ In using GPS for accurate localization:
  - It requires an unobstructed line of sight to the satellites
  - It depends on atmospheric conditions
  - It depends on the ability to receive (weak) radio frequency communications

Improving the Quality of GPS

- ✓ Mitigation of the measurement errors is simple: Errors are similar for users located not far from each other and change slowly in time
- ✓ Satellite geometry improvements

Differential GPS

- ✓ Differential GPS is a technique for correcting GPS signals by using a nearby GPS receiver located at a known accurately surveyed position
- ✓ A network of ground-based DGPS transmitters are in place, sending signals using radio frequencies between 285 kHz and 325 kHz

VISION SYSTEMS

Overview

✓ Still Cameras

- Very cheap
- Standard
- B&W or Color
- Produce modest amounts of data
  - (640 x 480) px/frame x (8 – 16 bits/px) = 2.4 – 4.8 Mbits/frame

✓ Video Cameras

- Cheap
- Standard
- Produce highest bandwidth of data
  - 30 frames/s x (640 x 480) px/frame x 16 bits/px = 140 Mbits/s

Overview

✓ Monocular Vision

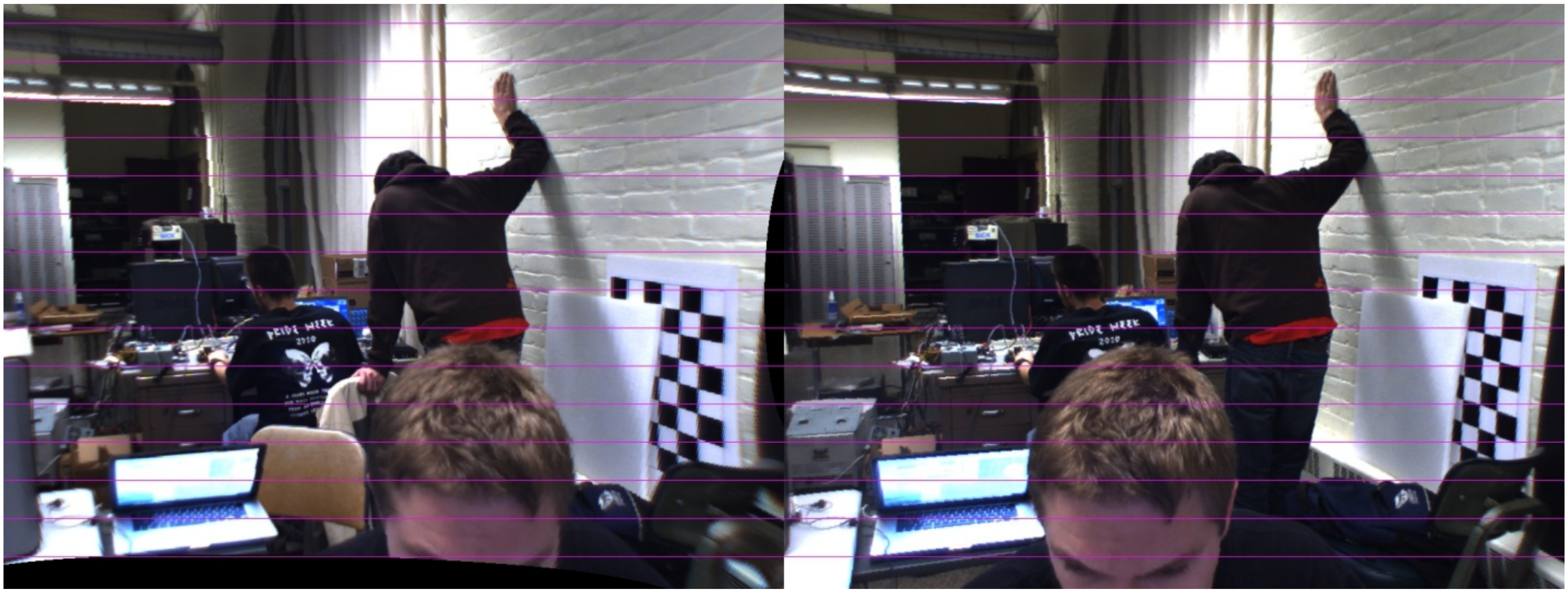
- Part identification
- Part position
- Quality checking

✓ Stereo (Binocular) Vision

- Depth or occupancy map
- Structure from motion
- Matching and triangulation
- Pose estimation
- Object and scene recognition
- Visual simultaneous localization and mapping

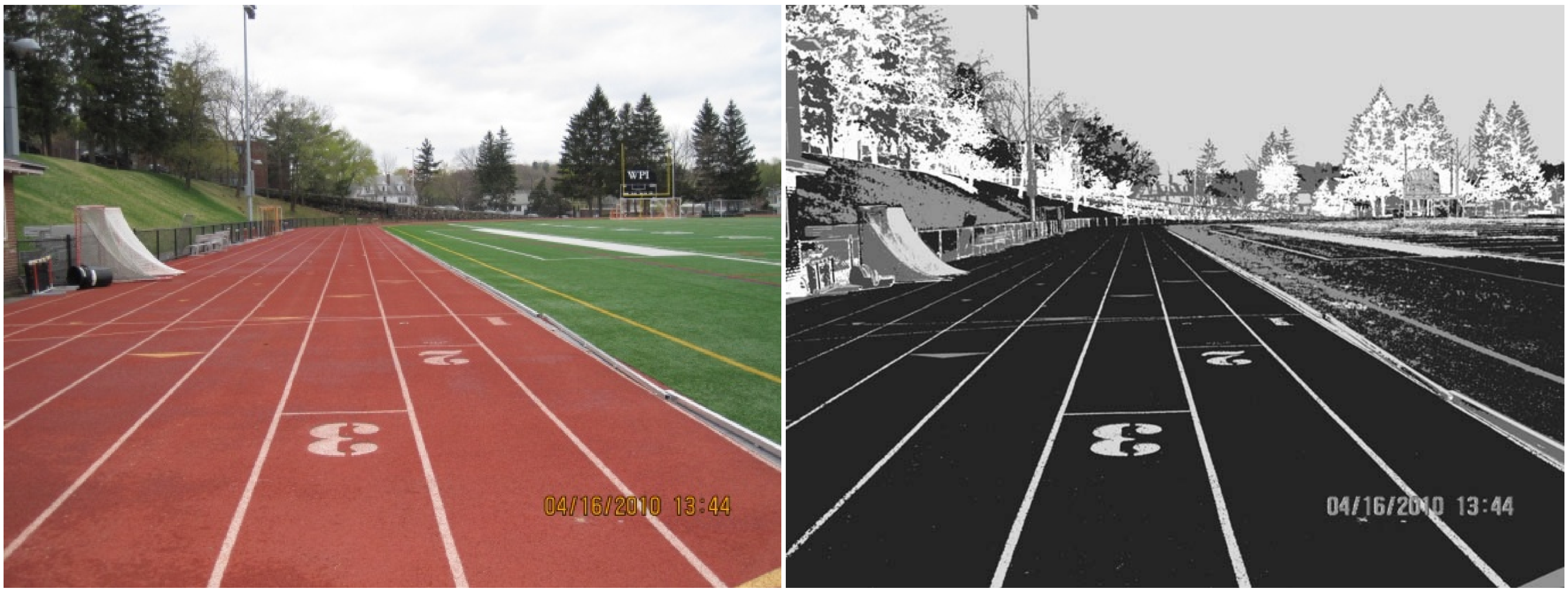
Example: Camera Calibration

Example: Image Rectification



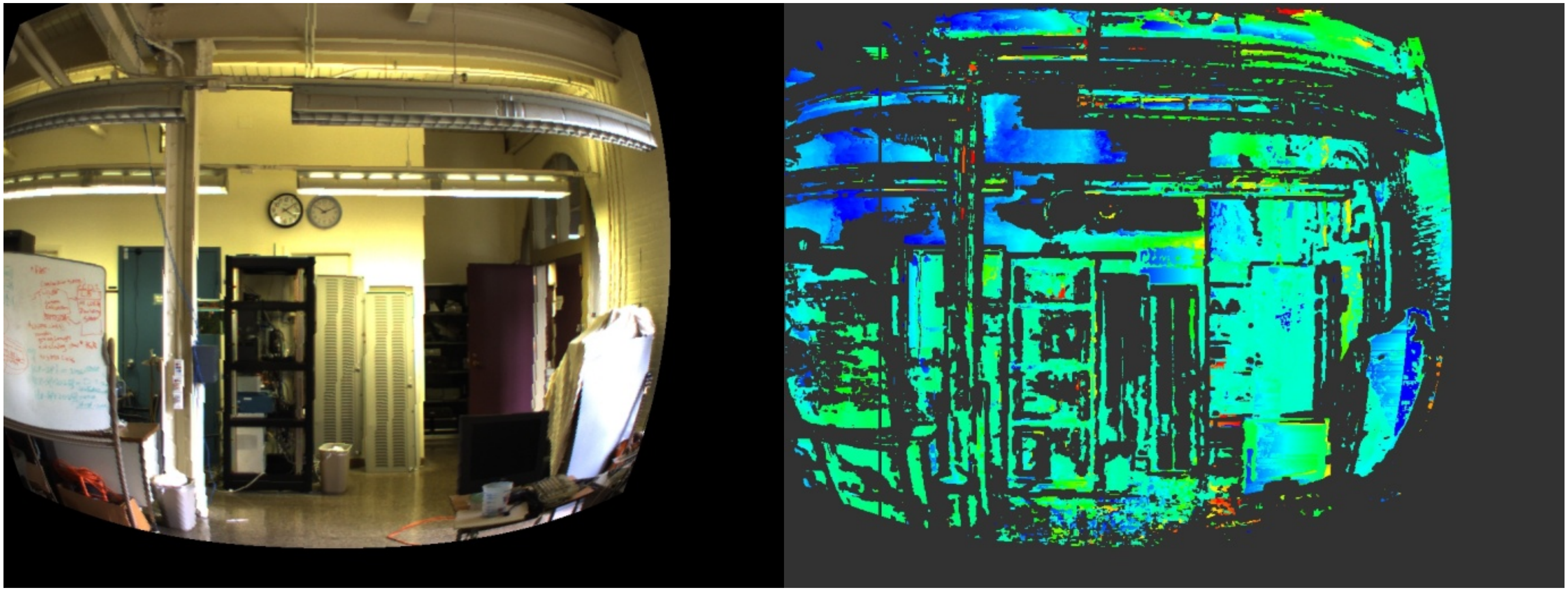
Example: Image Segmentation

Example: Image Clustering



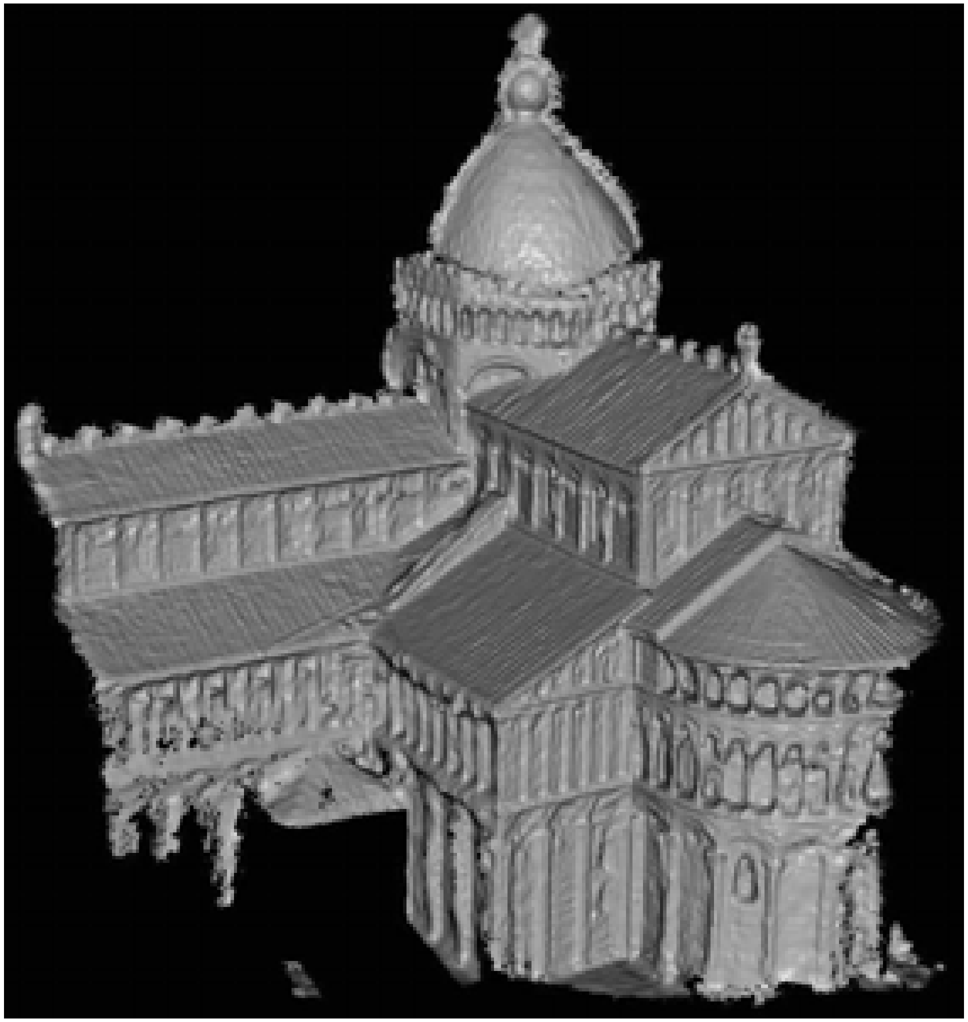
Example: Image Clustering

Example: Disparity Map

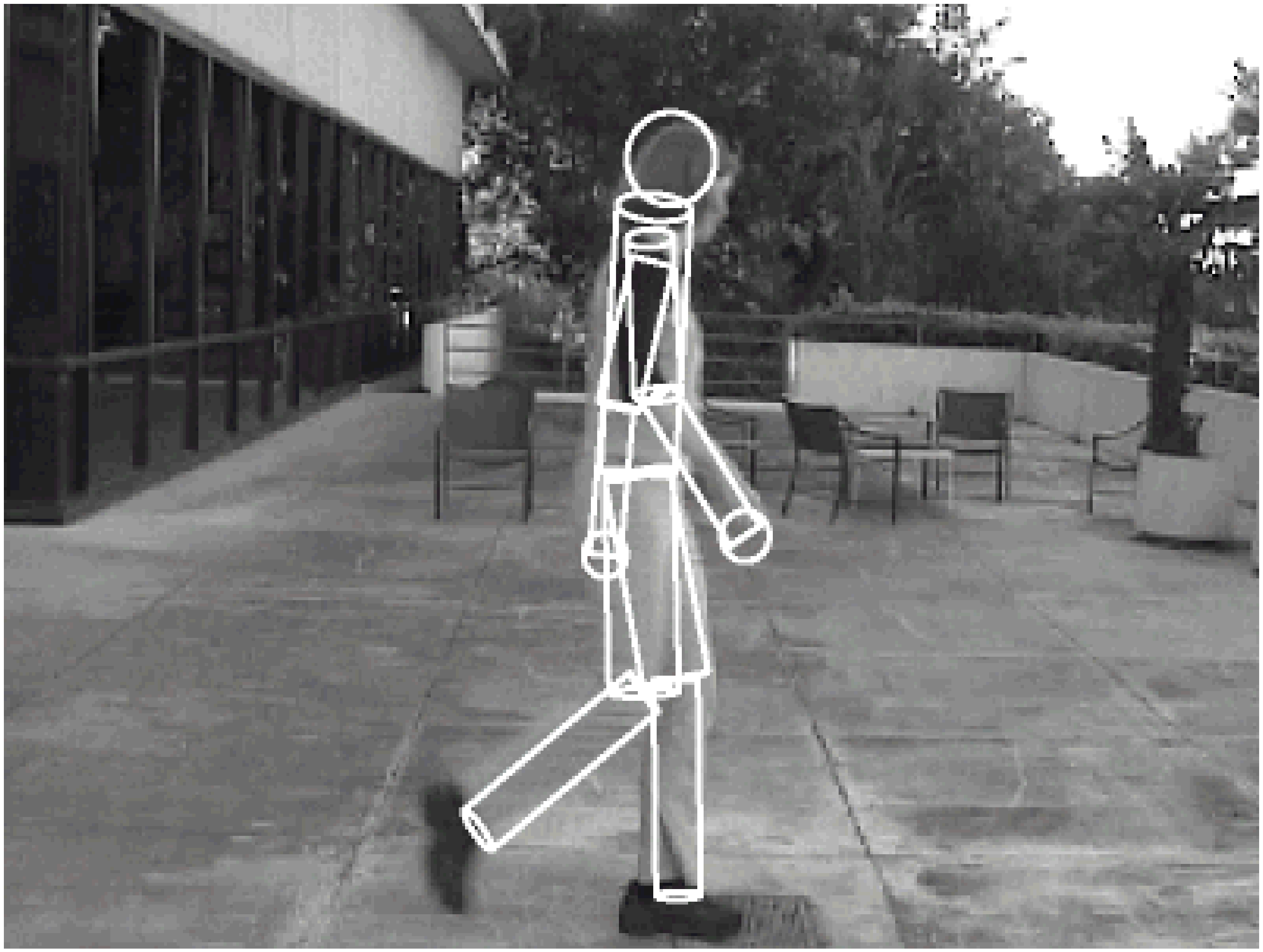


Structure from Motion

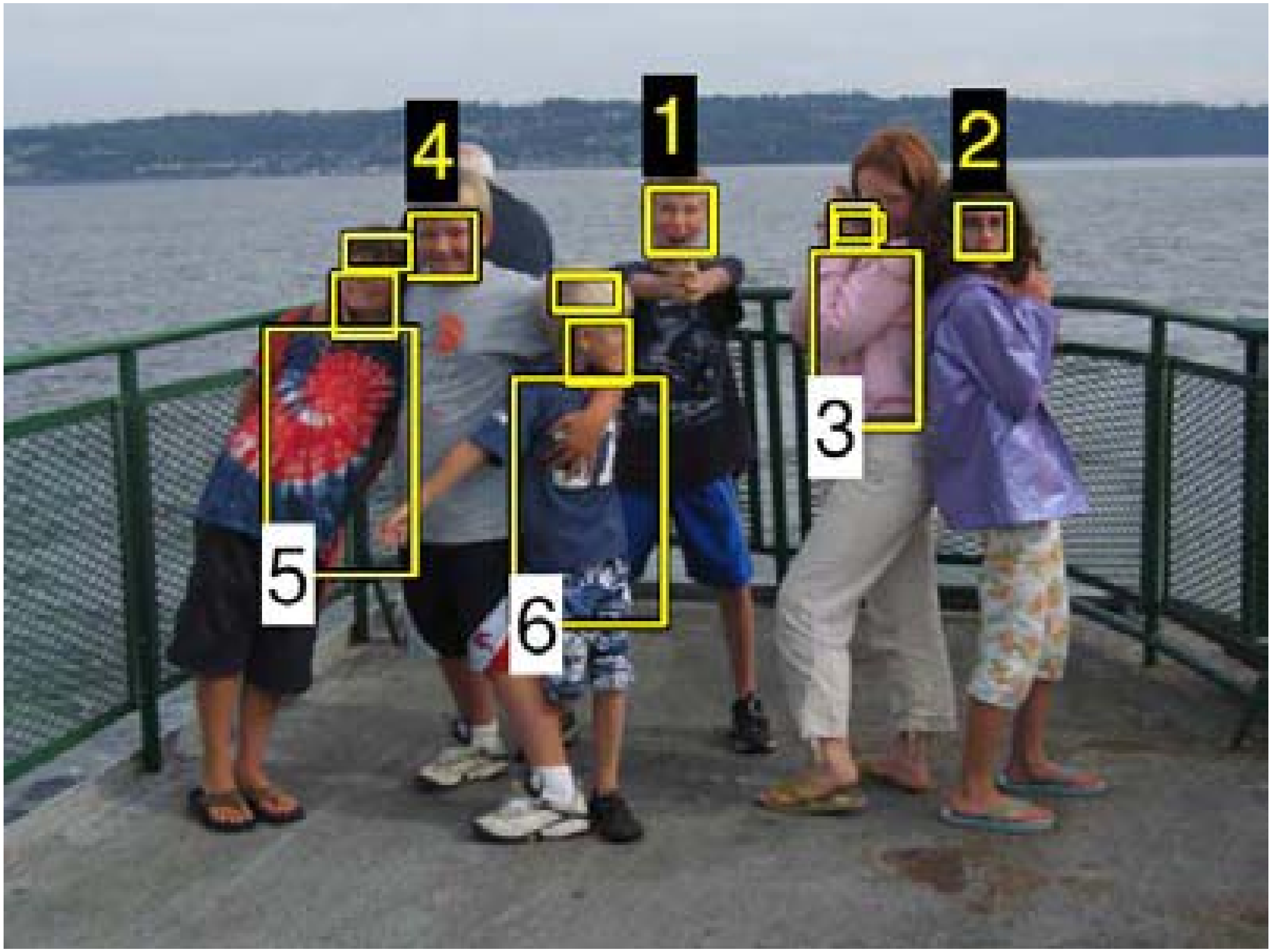
Stereo Matching Algorithms



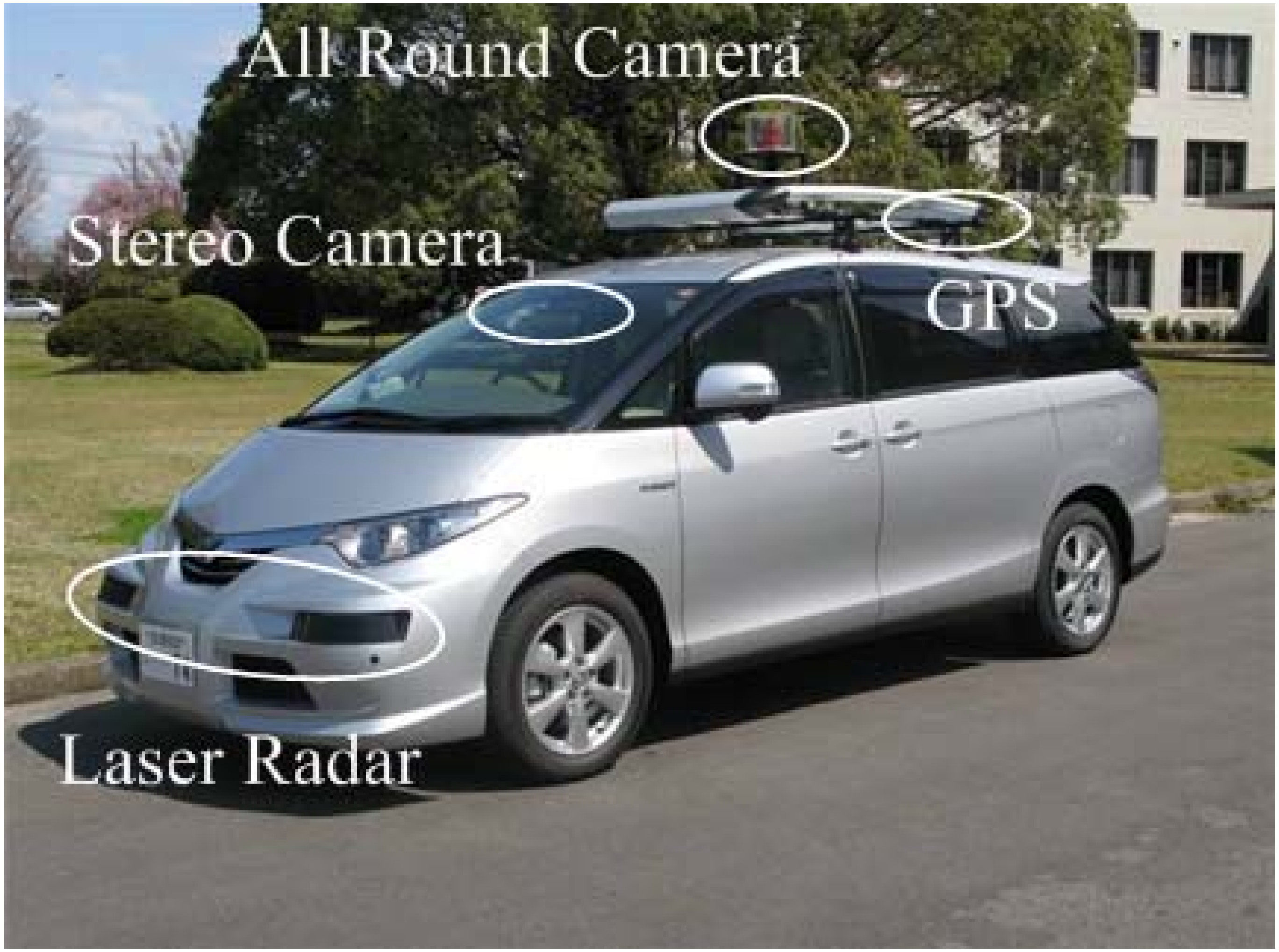
Person Tracking



Face Detection



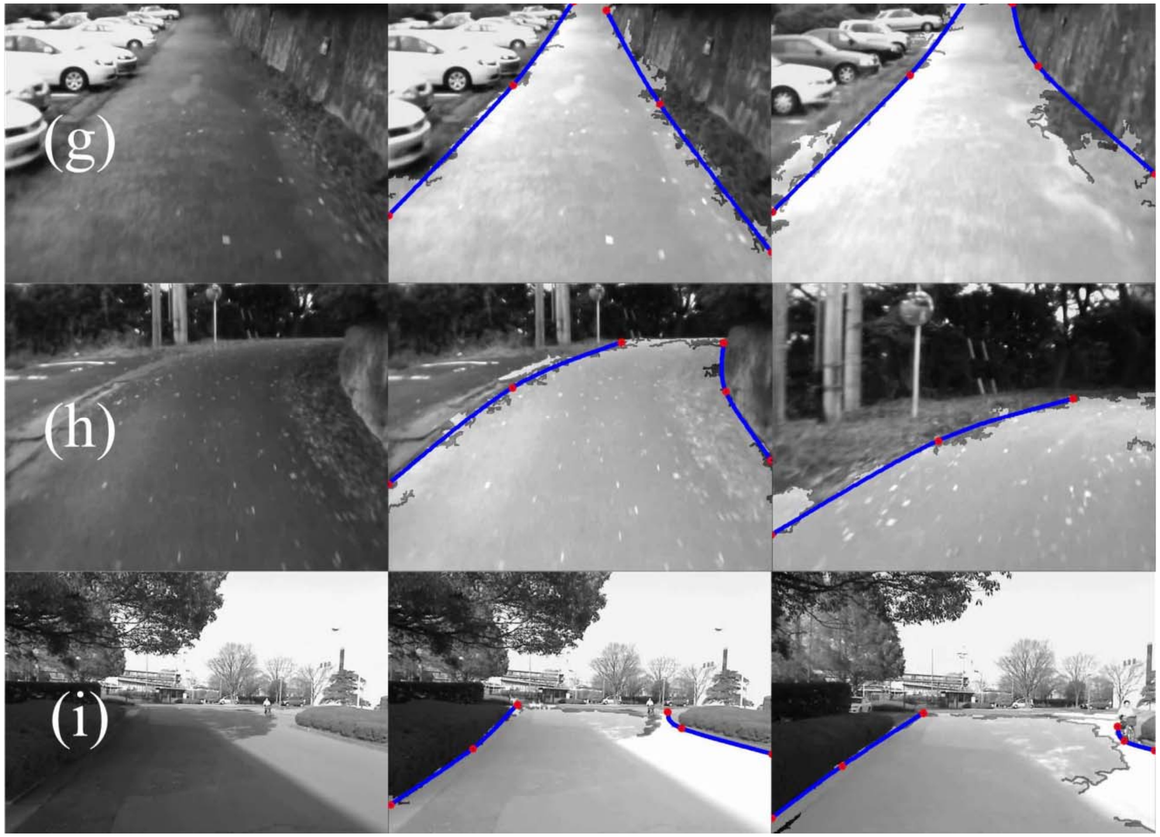
An Application



An Application

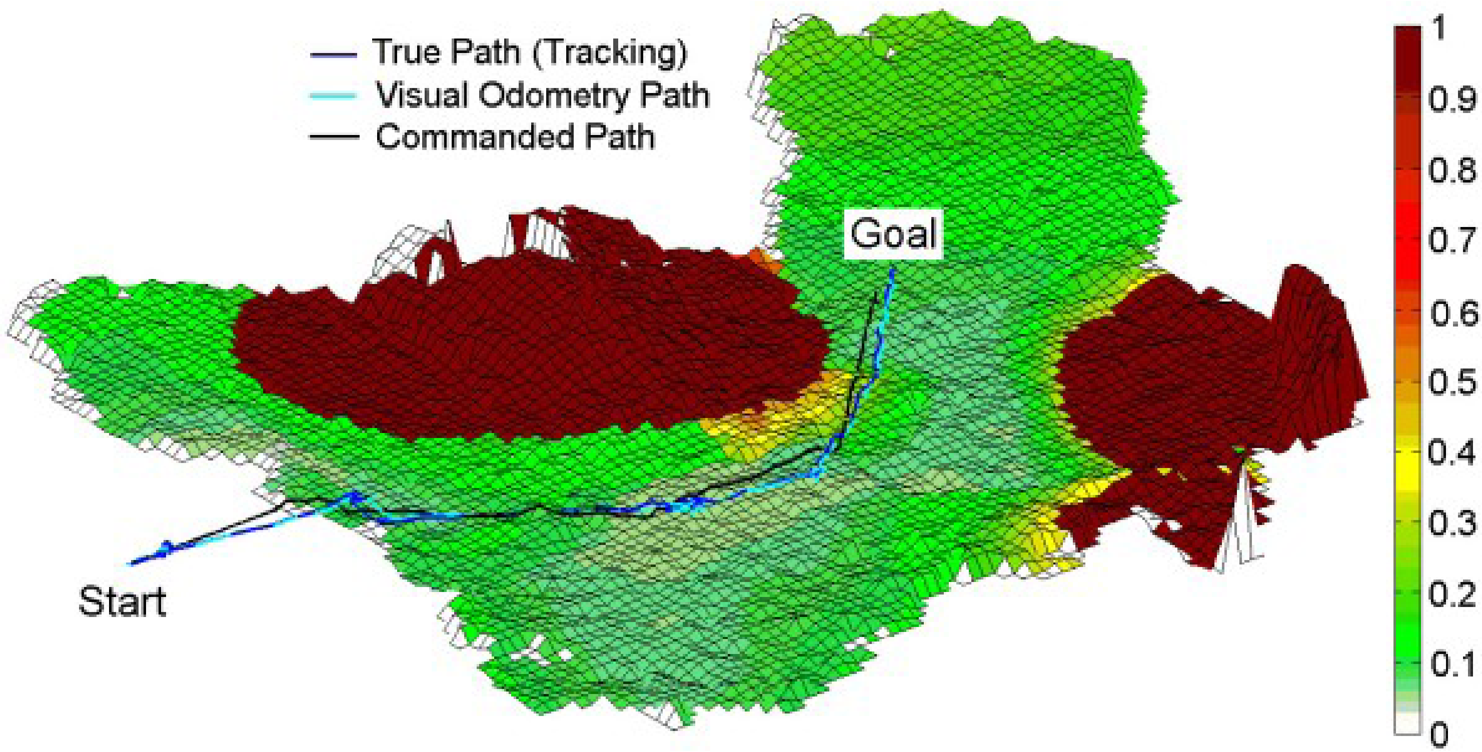
An Application

An Application



Another Application

Another Application



Example: Sensor accuracy

A linear displacement sensor ideally generates 1 mV per 1-mm displacement; However, in the experiment, a displacement of 10 mm produced an output of 10.5 mV. Calculate the sensor's absolute inaccuracy and relative inaccuracy.

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