Sensors for autonomous vehicles

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Problems with mobility

Autonomous Navigation
- "Where am I?" - Localization
- "Where have I been" - Map building
- "Where am I going?" - Path planning
- "How do I get there?" - Path tracking

Additional problems:
- "Will I hit anything?" - Obstacle detection
- "What will I hit?" - Classification
- "How can I avoid it?" - Obstacle avoidance

Sensors are essential

1 Object sensors for detection and identification
2 Pose sensors for localization

Object sensors

- Ultrasonic sonars
- Regular cameras
- Laser scanners
- 3D cameras
- Radars

Ultrasonic sonars

- Calculate distance based on the time of flight $t$:
  \[ d = \frac{1}{2} c t \]
- $c = c_0 + 0.6 T$
- $c_0 = 331$ m/s
- $T$: temperature in degrees Celsius
- Sensitive to dirt
- WIDE lobe
- Not very suitable for heavy outdoor use

* Emits a "chirp" (50 KHz) and "listens" for bounce back
* Used to determine range based on time of flight
* The object can be anywhere on the lobe perimeter
Regular cameras

- An image is a huge array of values of individual pixels
- Taken individually, these numbers are almost meaningless
- A robot needs information like "object ahead", "table to the left", or "person approaching" to perform its tasks

Computer Vision

- is the conversion of low level information picture information into high level information
- Separate field of study from robotics
- Includes analysis of signals from:
  - cameras
  - thermal sensors
  - X-ray detectors
  - laser range finders
  - synthetic aperture radar

Computer Vision

- Segmentation
  (where are the physical objects?)
- Classification
  (what are these objects?)
- 3D reconstruction
  (estimating ranges from 2D pictures)
- ...

Range from Vision

- Stereo camera pairs
- Light stripers
- Laser scanners
- 3D cameras

Stereo Camera Pairs

- A 3-D structure is computed from two or more images taken from different viewpoints
- Same technique as humans and animals use
- Heavy computations
- Delicate hardware

Laser Scanner

- Measures distance in a plane
- 181 (or 361) thin laser beams are emitted in a plane
- The time of flight of the signal is measured
- Max distance: 50m
- Resolution: 5cm
- Most often eye safe
### Laser Scanner

**Example:**

- Laser scanner: photo coverage

### 3D Laser scanner

**Riegl LMS-Z210**

- 3D laser scanner
- Measurement range up to 150-350 m depending on reflectivity
- Minimum range 2 m
- Measurement accuracy typ. +/- 2.5 cm
- Eye safety Class 1 for the scanned beam

### 3D Camera

- **CSEM SwissRanger**
  - (two other manufacturers exist)
  - Works like this:
    - Illuminates the scene with frequency modulated infrared light
    - Measures the phase shift of reflected light
    - This gives distance for each pixel
    - Reconstructs the relative xyz coordinates
  - Maximum range of 7.5 m
  - 144 x 176 pixels
  - Field of view: 40 degrees
  - Frame rate ~ 30 Hz
  - No moving parts (except for a fan)
  - 5000 euro

### Radar

- **Principle of radar:** The radar emits a radio signal (green) which is scattered in all directions (blue). The “time-of-flight” $t$ for the signal, back to the radar gives the distance $d$:
  
  $d = \frac{c t}{2}$

- Typically used in ships and airplanes
- Also as robot sensors:

- **CSEM Radar**
  - If the object moves, the frequency of the scattered wave changes.
  - A doppler radar measures the shift in frequency and computes the speed (in addition to distance)
  - Ignores all stationary objects
  - Used as back-up alarms and also as robot sensors
Radar

Sequential Lobing Radar (Tyco)
- Normally used as frontal radar for cars
- Can track 10 obstacles closer than 30 m
- Range calculated by time of flight
- Bearing calculated by comparing two different patterns sent out by the antenna

Sensor fusion
- Most object sensors are noisy and do not give crisp information about the presence of objects or pose
- Common to use a probabilistic approach: Each sensor readout gives a probability for objects occupying areas or for a certain pose
- Many readouts are fused into a combined opinion

An occupancy grid
is used to fuse object sensor readings and to create a map of the surrounding terrain.

 Sensors for localization
- A little more than “Where am I?”
- A vehicle has (at least) 6 degrees of freedom (DOF) expressed by the pose: $(x, y, z, \phi, \theta, \psi)$
  - Position = $(x, y, z)$
  - Attitude = roll, pitch, yaw = $(\phi, \theta, \psi)$
  = $(\text{phi, theta, psi})$

Pose

Definitions:
- Roll (a.k.a. “bank angle”) $\phi$: the angle between $y$ and the $x$-$y$ plane. $-\pi < \phi < \pi$
- Pitch (a.k.a. “elevation”) $\theta$: the angle between $x'$ and the $x$-$y$ plane. $-\pi < \theta < \pi$
- Yaw (a.k.a. “heading” or “azimuth”) $\psi$: the angle between $x$ and the projection of $x'$ on the $x$-$y$ plane. $-\pi < \psi < \pi$

The signs of the angles are defined in a right-handed coordinate system.

Using the Right-Hand Rule
To remember positive and negative rotation directions:
- Open your right hand
- Stick out your thumb
- Aim your thumb in an axis positive direction
- Curl your fingers around the axis
- The curl direction is a positive rotation

<table>
<thead>
<tr>
<th>Roll</th>
<th>Pitch</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. X-axis rotation</td>
<td>b. Y-axis rotation</td>
</tr>
<tr>
<td>c. Z-axis rotation</td>
<td>Yaw</td>
</tr>
</tbody>
</table>
**Pose sensors**

**Absolute:**
- GPS
- 

**Dead reckoning (relative):**
- Wheel odometry
- Accelerometers
- Gyroscopes

**GPS**
- Delivers position for a moving receiver:
  - Latitude, Longitude, Altitude
  - Speed and direction of movement can be estimated

**Dead reckoning**
Relative motion: Advance previous pose through displacement information:
- The simplest kind is called *odometry*:
  - Steering angle and velocity from actuators and shaft encoders.
- Accelerometers:
  - Use Newton's 2nd law: \( F = ma \) where \( a \) is the second derivative of the displacement, i.e. changes in \( (z,y,z) \).
- Gyroscopes:
  - Measures rotations, i.e. changes in \( (\phi, \theta, \psi) \)
- Cameras
- Laser scanners

**Wheel Odometry**
- Compute changes in the 2D-pose \((x,y,\theta)\) from steering angle and velocity
  - Steering angle from angle sensor
  - Velocity from shaft encoders or speed sensor
- Translate steering angle and velocity to \((x,y,\theta)\): Kinematics equations!
- Problems with wheel odometry:
  - The wheels move but not the robot (spinning)
  - The robot moves but not the wheels (slipping, sliding)
  - The ground is not flat
Causes drift!

**Shaft encoders**
Counts rotation steps for the wheels or engine

**Localization with odometry**

![Graph showing odometry position compared to GPS and position error in odometry after a time T](image-url)
**Dead reckoning**

**Accelerometers**
- A variant of "Dead reckoning" for measuring change in position (x, y, z)
- Common in airplanes, missiles and sub-marines since the 50’s.
  1. $\mathbf{F}$ is measured with 3 accelerometers
  2. $\mathbf{F} = m \mathbf{a}$
  3. Compute displacement by integrating twice $a$ twice:

**INS (Inertial Navigation Systems)**
- 3 accelerometers and 3 gyroscopes
- Measures changes in the pose (x, y, z, $\phi$, $\theta$, $\psi$)
- Good accuracy for short periods
- I.e. same problem as wheel odometry, but not sensitive to slipping and sliding

**Gyrosopes**
- Measures rotation with one, two or three DOF
- The inertia of the spinning wheel gives a reference for rotations
- Estimates ($\phi$, $\theta$, $\psi$) by summing up gyroscope rotations
- Fiber optical or solid state

**Ground Speed Radar**
Measures the real ground speed
Change in position can be computed

**Localization with Laser scanners**

**Absolute localization using laser**
Manually drive the path
Save laser snapshots and laser scanner poses in a database
Absolute localization using laser

Autonomously repeat the path
At each step:
1. Take a snapshot
2. Find the most matching snapshot in the DB
3. Find the optimal $\Delta x, \Delta y, \Delta \Phi$
4. Estimate pose $(x, y, \Phi)$ of robot

Other pose sensors

- **Mechanical tilt sensors**
  - Measures absolute attitude $(\phi, \theta)$
- **Magnetic compass**
  - Measures the earth magnetic fields along 3 axes. This gives three angles
  - Very sensitive to metal objects!