Mobile & Service Robotics

Sensors for Robotics – 2
Sensors for mobile robots

- Sensors are used to perceive, analyze and understand the environment around the robot.

- Problems: measurements may change due to the dynamic nature of the environment and they may be affected by a significant level of noise.

- Examples:
  - Surfaces with different and varying sound/light absorption/reflection properties.
  - Variability of light condition (scene illumination).
  - Sensitivity of measurements depending on robot pose.
Sensor types

1. Encoders and resolvers
2. Heading sensors, compasses
3. Gyroscopes
4. Beacons
5. Distance/proximity sensors
6. Accelerometers/Inertial Measurement Units (IMUs)
7. Vision (monocular, stereo)
Encoders

- **Encoders** measure the angular position and speed of the motors acting on the robot wheels.

- Velocity measurements are then integrated to provide an odometric estimate of the robot pose.

- Approximate pose is defined in the local reference frame.
Encoders

Light rays

Light source

Transparent slits

Rotating Disk

Receiver
Encoders

Incremental

Absolute

notch
Encoders

Source

Receiver

Electronics

Disk

Shaft

Source

Receiver

Electronics

Disk

Shaft
A resolver is a rotary electrical transformer used to measure rotations. The most common type of resolver is the brushless transmitter resolver.

It looks like a small electrical motor having a stator and rotor.

The stator portion of the resolver has three windings: an reference or exciter winding and two two-phase windings (labeled "SIN" and "COS").

The reference winding is the primary (fixed) winding of a turning (rotary) transformer and is excited by a sinusoidal electric current, which induces current in the rotor without a direct electrical connection, thus there are no wires to the rotor limiting its rotation and no need for brushes.

The two other windings in the stator are configured at 90 degrees from each other.

The two two-phase windings, fixed at right (90°) angles to each other on the stator, produce a sine and cosine feedback current.

The relative magnitudes of the two-phase voltages are measured and used to determine the angle of the rotor relative to the stator.
Resolvers

Resolvers

Terminal protection cover (Resin molded part)

Insulator (Resin molded part)

Rotor (Pressed part)

Terminal (Pressed part)

Stator (Pressed part)

Winding part (Copper)
Inertial sensors

- Inertial sensors are a class of sensors that measure the derivatives of the robot position variables.

- This class of sensors includes heading sensors, as well as gyroscopes and accelerometers.

- Heading sensors measure the horizontal or vertical angle referred to a given direction.

- In this group belong inclinometers, compasses, gyrocompasses.

- They provide an estimate of the position if used together with speed measurements.

- The above procedure is also called dead reckoning and is a characteristic of maritime navigation.
Compasses

- Compasses are known since the ancient times
- They are affected by the Earth magnetic field (absolute measurement)
- Physical measurement methods: mechanical (magnetic needle), Hall effect, magnetostrictive effect, piezoelectric

Piezoelectric resonators have been used as standard clocks in recent electronics technologies because of their sharp resonance profiles. We propose a magnetic field sensor consisting of a piezoelectric resonator and magnetostrictive magnetic layers. It is verified that its resonance frequency changes in a magnetic field with sensitivity high enough to detect terrestrial magnetic field. So, it is useful as an electronic compass that is in great demand from the mobile telecommunication technology. The advantage of this sensor is that it can readily be downsized maintaining a high S/N because it detects an external field through change of the resonance frequency rather than the analogue output.

- Limitations
  - The Earth magnetic field is rather weak
  - The measurement is easily disturbed by near metallic objects
  - Is rarely used for indoor navigation
Inclinometers

- Inclinometer are instruments for measuring angles of tilt, elevation or depression of an object wrt local gravity vector.
- Inclinometers measure both inclines (positive slopes, as seen by an observer looking upwards) and declines (negative slopes, as seen by an observer looking downward).
- Sensor technologies for inclinometers include accelerometer, capacitive, electrolytic, gas bubble in liquid, and pendulum.
A classic mechanical gyroscope is a massive rotor suspended in light supporting rings called “gimbals” that have nearly frictionless bearings and which isolate the central rotor from outside torques.

At high rotational speeds, the gyroscope maintains the direction of the rotation axis of its central rotor, since, in the absence of external torques, its angular momentum is conserved both in magnitude and in direction.
Gyroscopes

- Gyroscopes provide an absolute measurement, since they maintain the initial orientation with respect to a fixed reference frame.

- They can be mechanical or optical.

  - Mechanical
    - Standard (absolute)
    - Rated (differential)

  - Optical
    - Rated (differential)
Mechanical gyroscopes

Angular moment is conserved

Rotation axis

Wheel

Wheel bearing

Outer pivot

Outer gimbal

Inner pivot

Inner gimbal

$\Gamma$

$\Gamma \omega$

$\omega$
Mechanical gyroscopes

- Concept: inertial properties of a rotor that spins fast: *precession phenomenon*

- Angular moment is conserved and keeps the wheel axis at a constant orientation

- Negligible torque is transmitted to the external mounting of the wheel axis

- Reaction torque $\tau$ is proportional to the rotation speed $\omega$, the inertia $I$ and the precession velocity $\Omega$

  \[ \tau = I\omega \Omega \]

- If the rotation axis is aligned along the N-S meridian, the Earth rotation does not influence the measurements

- If the rotation axis is aligned along the E-O meridian, the horizontal axis measures the Earth rotation
Differential gyroscopes

☐ An angular velocity is measured instead of an angle

☐ Same construction concept, but the cardanic joints (aka *gimbals*) are constrained by a torsion spring

☐ Other gyroscopes use the Coriolis effect to measure the orientation variation
Differential gyroscopes

- The frame and resonating mass are displaced laterally in response to Coriolis effect. The displacement is determined from the change in capacitance between the Coriolis sense fingers on the frame and those attached to the substrate.
Optical gyroscopes

- Base on the **Sagnac** effect
- Two monochromatic laser rays are produced and injected into an optical fiber coiled around a cylinder
- One ray turns in one sense, the other in the opposite sense
- The ray that turns in the same sense of the rotation, covers a shorter path and shows a higher frequency than the other; the frequency difference between the two rays is proportional to the cylinder angular speed
- Solid state sensors; directly integrable on silicon together with the electronic circuits
Gyrocompasses

- A **gyrocompass** is similar to a gyroscope
- It is a compass that can find true north by using an electrically powered, fast-spinning gyroscope wheel and frictional or other forces in order to exploit basic physical laws and the rotation of the Earth.
- Gyrocompasses are widely used on ships. Marine gyrocompasses have two main advantages over magnetic compasses
  - they find *true north*, i.e., the point of the Earth's rotational axis on the Earth's surface, an extremely important aspect in navigation
  - they are unaffected by external magnetic fields which deflect normal compasses, such as those created by ferrous metals in a ship's hull
Gyrocompasses
INS example

Inertial measurement unit of S3 Missile, Museum of Air and Space Paris, Le Bourget (France)
Inertial Measurement Units (IMUs)

- Inertial Measurement Units are integrated sensors that usually include 3-axis accelerometers, gyroscopes and sometimes also magnetic (or other forms of) compasses.
- IMUs where mainly used for missile and aircraft guidance and navigation: in this sense they are known as inertial navigation systems (INS).
- INS include at least a computer and a platform or module containing accelerometers, gyroscopes, or other motion-sensing devices.
- INS is provided with its initial state from another source (a human operator, a GPS satellite receiver, etc.), and thereafter computes its own updated position and velocity by integrating information received from the motion sensors.
- The advantage of an INS is that it requires no external references in order to determine its position, orientation, or velocity once it has been initialized.
Inertial-navigation systems are used in many different moving objects, including vehicles, such as aircraft, submarines, spacecraft, and guided missiles.

However, their cost and complexity make impractical to use them on smaller vehicles, such as cars or mobile robots.

IMUs are a simpler version of INS, with dimensions that are now in the range of 5 x 5 cm and with a cost that is much smaller than INS (around 800-1,000 €).
An accelerometer is a device that measures the proper (absolute) acceleration of the device, measuring the acceleration forces.

These forces may be static, like the constant force of gravity, or they could be dynamic, caused by moving or vibrating the accelerometer.

Accelerometers can be essentially understood considering spring-mounted masses.

\[
F = ma \\
F = kx \\
a = \frac{kx}{m}
\]
Accelerometers

![Diagram of an accelerometer]

- Seismic Mass (M)
- Quartz Crystals (k)

**Equations:**
- $1/3 f_n$
- $f_n$

**Log f vs Magnitude Plot:**
Micromachined (MEMS) accelerometer
Accelerometers

- An accelerometer measures accelerations along one direction, so usually there are three of them placed at mutually orthogonal axes.

- Gravity acceleration may be useful, as in inclinometers, or noxious, as when only the proper acceleration of the frame (velocity variation) must be computed. In this case gravity must be cancelled.

- Accelerometers are unsuited to estimate velocity or position; they accumulate large drift errors due to many causes; temperature sensitivity, hysteresis and bias are the most important.
Beacons

- They allow to guide systems with known absolute position. Are also called “landmarks” (artificial or natural)
  - Known and used since ancient times: i.e., sun, mountain tops, bell towers, lighthouses, etc.

- They are useful for indoor motion, where GPS use is impossible

- Rather expensive, since they require an infrastructure setting

- Not easy to adapt to variable environment conditions
GPS

GPS are not suited for indoor use and will not be treated in this course.
Distance Sensors

- Also known as range sensors, they measure “large” distances.
- Other type of sensors measure “small” distances (proximity sensors).
- They use the time-of-flight principle.
- Ultrasonic (sonar) or laser sensor are based on the sound or light speed that is a well known value.

\[ d = cT \]

- Distance (two ways)
- Wave speed (sound/electromagnetic)
- Time measured
Distance Sensors

- Speed of sound approx 0.3 m/ms
- Speed of light (in vacuum) 0.3 m/ns
- Rate $10^6$
- A distance of 3 m is equal to
  - 10 ms using sound waves
  - only 10 ns with a laser sensor
  - difficult to measure
  - laser sensor are expensive
Distance Sensors

- The quality of measurements depends on
  - Uncertain arrival time of the reflected wave (laser and sonar)
  - Uncertain time-of-flight (laser)
  - Aperture angle (sonar)
  - Interaction with surfaces (sonar and laser)
  - Variability of the speed (sonar)
  - Possible speed of the source (sonar)
Ultrasonic Sensors

- A package of sound (pressure) waves is generate and emitted the so called *chirp*
- Relation is simply:

\[ d = \frac{cT}{2} \]

- The sound speed in air is given by the following relation:

\[ c = \sqrt{\gamma R K} \]

where

\[ \gamma = \text{specific heat constant} \]
\[ R = \text{gas constant} \]
\[ K = \text{temperature in Kelvin} \]
Ultrasonic Sensors

Wave packet

integrator

Time of flight (sensor output)
Ultrasonic Sensors

- Used frequencies: 40-200 kHz
- Generated from a piezoelectric vibrating source
- Transmitter and receiver may be separated or not
- Sound is emitted in a conic shape
- Aperture angle 20°-40°
Encoders
Encoders

- Index grating
- Silicon solar cells
- Condenser lens
- Graduated disc with radial grating
- Miniature lamp
- Reference mark (reference pulse grating)
- Encoder shaft

Encoders with incorporated pulse shaping electronics
- Without interpolation
- 5-fold interpolation

Encoders without incorporated pulse shaping electronics
- Without interpolation
- 5-fold interpolation

Output signals
- Without interpolation
- With interpolation

Reference signal
- Measuring step with 4-fold evaluation
- Measuring step with 8-fold evaluation

NC
- 7, 8, 9
- 4, 5, 6
- 1, 2, 3
- 0, 7

NC
- 7, 8, 9
- 4, 5, 6
- 1, 2, 3
- 0, 7
Encoders

Notice what happens when the direction changes:
Mechanical gyroscopes