Principles of Safe Autonomy: Robot Sensors and Applications

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Outline

• Basics of Sensors
• Sensors in Robotics
• Robot Applications
Sensor

• Sensor?
  • Sensor is a device, module, machine, or subsystem whose purpose is to detect events or changes in its environment and send the information to other electronics, frequently a computer processor.

• Requirements for a good sensor
  • High sensitivity and selectivity, fast and predictable response, reversible behavior, high signal to noise ratio, compactness, low cost, immune to environment, easy calibration, stability, continuous operation without affecting original system
Various Sensors (1)

• Mechanical sensors
  • space- distance, angle, displacement, level, deformation,…
  • Time- Time, Lapse, Period,…
  • Movement- (Linear/Angular) Velocity/Acceleration, Vibration, Rotation, Flux,…
  • Force- Weight, Pressure, Torque,…
  • Others- Mass, Density, Viscosity, Elasticity, Hardness, Strength,…

• Electromagnetic
  • Electric- Voltage, current, power, charge, electric field, electric force,…
  • Magnetic- Magnetic field, Magnetic force, magnetic resistance, magnetic polarization,…
  • Electromagnetic wave – wavelength, frequency,…
  • Others- dielectric constant, resistivity, permittivity, permeability, polarizability
Various Sensors (2)

- **Optical**
  - Visible light: Intensity, Color, Polarization, Interference, Diffraction, Refraction, Reflection, ...
  - Infrared/Ultraviolet
  - Image
  - Other Fluorescence

- **Radiation**
  - Charged particle
  - Electron
  - E-M wave radiation

- **Acoustic**
  - Acoustic wave
  - Ultrasonic wave
  - Voice/noise

- **Thermal**
  - Heat
  - Temperature

- **Chemical**
  - Gas
  - Ion
  - Component
  - Humidity
  - Particulate/smoke

- **Biological**
  - Biomolecules
  - Cells
  - Biofunction
Sensors in a car

- Combo Sensor
- Steering-torque
- HVAC Sensor
- Steering Sensor
- Differential Non-Contacting Angle Sensor
- Mirror Sensor
- Wheel Speed Sensor
- Headlight Range Sensor
- Accelerator Pedal Angle Sensor
- Transmission Sensor
- Fuel Level Sensor
- Motor Position Sensor
- Chassis Level Sensor
Physical Principles of Sensing

• Electric Charges, Fields, and Potentials
• Capacitance (Capacitor, Dielectric Constant)
• Magnetism (Faraday’s Law)
• Induction
• Resistance
  • Specific Resistivity
  • Temperature Sensitivity
  • Strain Sensitivity
  • Moisture Sensitivity
• Piezoelectric Effect
• Pyroelectric Effect
• Hall Effect
• Seebeck and Peltier Effects
• SoundWaves
• Temperature and Thermal Properties of Materials
• Heat Transfer
• Light
Sensor Characteristics

- **Transfer Function**
  - Relationship between physical input signal and electrical output signal

- **Dynamic Range (Span or Full-Scale Input)**
  - The range of input signals which may be converted to electric output signals by the sensor

- **Sensitivity**
  - Ratio between a change in output signal and a change in input signal

- **Accuracy**
  - Uncertainty is the largest expected error between actual and ideal output signals
  - A percentage of full scale or absolute term

- **Resolution**
  - Minimum detectable signal fluctuation
Response & Recovery time

- **Response time**: the time it takes the sensor to reach 90% of its steady-state value after the introduction of the measurand.
- **Recovery time**: the time it takes the sensor to be within 10% of the value it had before exposure to the measurand.
- Typically the response times are much shorter than the recovery times.
- **Bandwidth**: how sensors respond at different frequencies. Higher bandwidth sensors can measure higher frequency motion and vibration.
Transfer Function

\[ X_r \]

\[ X_A \]

\[ C_1 \quad C_2 \quad C_3 \quad C_4 \]

- \( 0 \leq C \leq C_1 \): below the sensor response threshold level
- \( C_1 \leq C \leq C_4 \): complete sensor dynamic range
- \( C_2 \leq C \leq C_3 \): ideal sensor dynamic range (linear region of \( X_r \) vs. \( C \) curve)
- \( C_1 \leq C \leq C_2 \) and \( C_3 \leq C \leq C_4 \): nonlinear region of the sensor dynamic range
- \( C \geq C_4 \): saturation region of sensor
Example

- Air pressure sensor

Features

- Proprietary Honeywell technology
- Protected by multiple global patents
- Industry-leading long-term stability: ±0.25 %FSS
- Total Error Band (TEB): ±1.6 %FSS
- Industry-leading accuracy: ±0.25 %FSS BFSL
- High burst pressures
- Industry-leading flexibility
- Wide pressure range: 60 mbar to 10 bar | 6 kPa to 1 MPa | 1 psi to 150 psi
- Meets IPC/JEDEC J-STD-020D.1 Moisture Sensitivity Level 1 requirements
- Optional internal diagnostic functions
- Energy efficient
- Output: ratio metric analog; PC- or SPI-compatible 14-bit digital output (min. 12-bit sensor resolution)
- Small size: As small as 8 mm x 7 mm
- REACH and RoHS compliant
- Sleep mode option (see Technical Note)
- Temperature output option
- Liquid media option

Table 1. Absolute Maximum Ratings

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Min.</th>
<th>Max.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply voltage ($V_{supply}$)</td>
<td>-0.3</td>
<td>6.0</td>
<td>Vdc</td>
</tr>
<tr>
<td>Voltage on any pin</td>
<td>0.3</td>
<td>$V_{supply}$ + 0.3</td>
<td>V</td>
</tr>
<tr>
<td>Digital interface clock frequency:</td>
<td></td>
<td></td>
<td>Hz</td>
</tr>
<tr>
<td>SPI</td>
<td>100</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>PC</td>
<td>50</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>SSD susceptibility (human body model)</td>
<td>2</td>
<td>–</td>
<td>kV</td>
</tr>
<tr>
<td>Storage temperature</td>
<td>-40[·40°C]</td>
<td>85 [165°C]</td>
<td>ºC/ºF</td>
</tr>
<tr>
<td>Soldering time and temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead solder temperature (DIP)</td>
<td>4 s max. at 250 ºC [482 ºF]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak reflow temperature (Leadless SMT)</td>
<td>1 s max. at 250 ºC [482 ºF]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Absolute maximum ratings are the extreme limits the device will withstand without damage.

Table 2. Environmental Specifications

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humidity</td>
<td>0% to 95% RH, non-condensing</td>
</tr>
<tr>
<td>Vibration</td>
<td>15 g, 10 Hz to 2 Hz</td>
</tr>
<tr>
<td>Shock</td>
<td>100 g, 6 ms duration</td>
</tr>
<tr>
<td>Life</td>
<td>1 million pressure cycles minimum</td>
</tr>
<tr>
<td>Solder reflow</td>
<td>J-STD-020-D1 Moisture Sensitivity Level 1 (unlimited shelf life when stored at ≤20 ºC/68 ºF)</td>
</tr>
</tbody>
</table>

*Life may vary depending on specific application in which the sensor is used.*
Table 5. Operating Specifications

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply voltage Na meas (^{1,2,3})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Vdc</td>
</tr>
<tr>
<td>3.3 Vdc</td>
<td>3.0</td>
<td>3.3</td>
<td>3.6</td>
<td>3.0</td>
<td>3.3</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>5.0 Vdc</td>
<td>4.75</td>
<td>5.0</td>
<td>5.25</td>
<td>4.75</td>
<td>5.0</td>
<td>5.25</td>
<td></td>
</tr>
<tr>
<td>Supply current:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td>3.3 Vdc</td>
<td>-</td>
<td>2.1</td>
<td>2.8</td>
<td>-</td>
<td>3.1</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>5.0 Vdc</td>
<td>-</td>
<td>2.7</td>
<td>3.8</td>
<td>-</td>
<td>3.7</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>Sleep mode option</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>1</td>
<td>10</td>
<td>-</td>
<td>1</td>
<td>10</td>
<td>(\mu)A</td>
</tr>
<tr>
<td>Operating temperature range (^4)</td>
<td>-40</td>
<td>-40</td>
<td>-65</td>
<td>-40</td>
<td>-40</td>
<td>-65</td>
<td>°C [°F]</td>
</tr>
<tr>
<td>Compensated temperature range (^5)</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>°C [°F]</td>
</tr>
<tr>
<td>Temperature output option (^6)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>°C</td>
</tr>
<tr>
<td>Startup time (power up to data ready)</td>
<td>-</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>ms</td>
</tr>
<tr>
<td>Response time</td>
<td>-</td>
<td>1</td>
<td>0.46</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>ms</td>
</tr>
<tr>
<td>Clipping limit</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>%/Supply</td>
</tr>
<tr>
<td>upper</td>
<td>2.5</td>
<td>-</td>
<td>97.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>lower</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>%/Supply</td>
</tr>
<tr>
<td>SP/PC voltage level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>%/Supply</td>
</tr>
<tr>
<td>low</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>80</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>high</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>%/Supply</td>
</tr>
<tr>
<td>Pull up on SDA/MSO, SCL/CLK, SS</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>kHz</td>
</tr>
<tr>
<td>Accuracy</td>
<td>-</td>
<td>-</td>
<td>±0.25</td>
<td>-</td>
<td>±0.25</td>
<td>±0.25</td>
<td>%/FSS, BPSL</td>
</tr>
<tr>
<td>Output resolution</td>
<td>0.03</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>%/FSS, bits</td>
</tr>
</tbody>
</table>

Digital Versions

Output (% of 2\(^{14}\) counts) = \[
\frac{80}{P_{max} - P_{min}} \times (Pressure_{applied} - P_{min}) + 10\%
\]
Sensors in Robotics
Sensors in Robots

• Internal Sensors
  • Getting data from the robot system itself
    • Position sensor, velocity sensor, acceleration sensors, Gyroscope, torque sensor, etc

• External Sensors
  • Getting data from the environment
    • Camera
    • Range sensors (IR sensor, laser range finder, ultrasonic sensor, etc)
    • Contact and proximity sensor (Photodiode, IR detector, RF sensor, touch sensor, etc)
  • Force sensor
Position Sensor: Potentiometer

- A three-terminal resistor with a sliding or rotating contact that forms an adjustable voltage divider.
- Pros: Simple, cheap
- Cons: Frictions, noisy signal, nonlinearity
Position Sensor: Optical Encoder

• An optical encoder is to measure the rotational position, speed and direction.
• It consists of a light beam, a light detector, and a rotating disc with slits.
• Optical encoder has become the most popular
  • Long life
  • Simple construction
  • Versatility
  • High accuracy and high resolution
• Typical resolutions of 2000 increments per revolution.
• Either relative or absolute
Incremental Encoder

• The rotary incremental encoder is the most widely used of all rotary encoders.
• An incremental encoder measures changes in position with two (or more) channels.
• The direction of rotation is determined by checking which phase of signals is leading.
  • If Phase A signals are leading, the rotation is in the clockwise direction.
  • If Phase B signals are leading, the rotation is the counterclockwise direction.
Incremental Encoder

- Resolution
  \[ s = \frac{360^\circ}{\text{Number of slits}} \]

- The smaller is the resolution, the better is the measurement.

- By counting the raising and falling edges, the resolution can be increased 4 times.
Absolute Optical Encoder

- Digital absolute encoders produce a unique digital code for each distinct angle of the shaft. An absolute encoder maintains position information when power is removed from the encoder.
Velocity Measurement

• Differentiate position

\[ \text{Velocity} = \frac{\Delta \text{Position}}{\Delta \text{Time}} \]

• Advantages: measurement without additional sensors, simple calculation

• Problems: noisy signals

• Solution: filters (low-pass filter, Kalman filter, etc.)
Accelerometer

• Most of accelerometers are based on Newton’s second law. An accelerometer behaves as a damped mass on a spring. When the accelerometer experiences an acceleration, the mass is displaced in the designed system. The displacement is then measured to give the acceleration.

• Sensing:
  • Piezoelectric
  • Capacitive
  • Magnetic

• Example: MEMS accelerometer
Gyroscopes

• A device used for measuring or maintaining orientation and angular velocity

• It is a spinning wheel or disc in which the axis of rotation (spin axis) is free to assume any orientation by itself. When rotating, the orientation of this axis is unaffected by tilting or rotation of the mounting, according to the conservation of angular momentum.

• Absolute measure for the heading of a mobile system
Inertial measurement unit (IMU)

• An electronic device that measures and reports a body's specific force, angular rate, and sometimes the orientation of the body, using a combination of accelerometers, gyroscopes, and sometimes magnetometers.
Robot Applications
The Atlas robot

• Human size, 185 kg
• 30 DoF
  • 6 for each leg, 7 for each arm, 3 for the spine, 1 for neck pitch
• Mostly hydraulic actuators, electric forearms
• Onboard power and computing
• Joint servos controlled at 1 kHz
Onboard sensors

- LiDAR
- Stereo vision
- Pressure Sensors (2X)
- Pelvis IMU
- 3-axis F/T $F_z, M_x, M_y$
- LVDT
Actuator

- 15 linear actuators
- 13 rotary actuators (arms and Back Z)
- All hydraulic
Joint Mechanism

- Linear actuators + mechanical transmission for most joints
  - Back z degree of freedom has rotary actuator
- High performance electrohydraulic servovalves
- Position sensing:
  - Linear variable differential transformer (LVDT)
  - MR encoder (back z)
  - Potentiometer (arms)
- Force sensing
  - Pressure sensors
Joint Torque

- Linear force, $f$, estimated via pressure sensors $(P_1 \cdot A_1 - P_2 \cdot A_2)$
  - $A_1 \neq A_2$, max. force is asymmetric
- Torque given by $\tau = f \cdot TR$, where $TR$ is the transmission ratio of the linkage
  - Max. torque is configuration dependent
  - Torque estimates do not take into account friction

**Linear Actuator**

- Actuator Body
- Piston
- Servo valve
- Supply, Return
Hopping Robot

- LEAP mechanism
  - Stiffness (2060 N/m)
  - Increase input voltage (48V)
  - Temperature sensor

- Actuated gimbal hip
  - Two servo motors

- Components in “Torso”
  - Seven 11.1 V Li-Po Batteries
  - Microcontroller (TI LAUNCHXL-F28377S)
  - IMU (Xsens MTi-3- 8A7G6-DK)
Results

- Up to 11 hops
- Problems
  - Ignoring mass distribution
  - No “ground truth”
Difficulties in state estimation

- Data acquired
  - Vicon MX series (16 cameras, 120 fps)
  - Hand-held
  - Robot hopping