Basic Terms

• **Transducer**: a device which converts one form of energy to another

• **Sensor**: a transducer that converts a physical phenomenon into an electric signal—an interface between the physical world and the computing world.

• **Actuator**: a transducer that converts an electric signal to a physical phenomenon
From Physical Process to Digital Signal

- Sensor
- Precision amplifier
- Analog to digital converter
- Signal processing
- Digital to analog converter
- Monitoring

A Measurement and Control System

- Transducer
- Signal Conditioning
- Transmitter
- Display
- Actuator
- Sensor
- Orders Transmission
- Manual Control
- Objectives
- System, Plant or Process
- Controller
- Supervisor

Sensor Devices
**Sensor-to-Signal Interface**

- Action of environment on a sensor causes it to generate an electrical signal directly
  - voltage source (V)
  - current (I) or charge (Q) source

- Action of environment on sensor changes an electrical parameter that we can measure
  - resistance changes: \( V \sim I \)
  - capacitance changes: \( V \sim \int I \, dt, I \sim \frac{dV}{dt} \)
  - inductance changes: \( V \sim \frac{dI}{dt}, I \sim \int V \, dt \)

**Signal Conditioning**

- Filter for expected frequency regime
- Subtract DC offset ("zeroing")
- Amplify or attenuate signal ("scaling")
- Linearize relationship between measured and observed electrical parameter
  - now usually done in software after ADC
- ...

**Analog-to-Digital Converter (ADC)**

- Many different principles
- Often integrated with microcontrollers
  - in some types, e.g., "successive approximation", the CPU participates in the conversion process
    - normally want to avoid this
- All involve trade-offs of speed (conversion time), resolution (number of bits), and cost
  \[ Q = \frac{E_{\text{ref}}}{2^N} = \frac{E_{\text{ref}}}{N} \]
- "Flash converter" is the fastest, has the lowest resolution and the highest cost
  - required for video digitization
(One) Classification of Sensors

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Classes</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power supply</td>
<td>Modulating</td>
<td>Thermistor*</td>
</tr>
<tr>
<td></td>
<td>Generating</td>
<td>Thermocouple**</td>
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<td>Output signal</td>
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<td>Potentiometer</td>
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<td></td>
<td>Digital</td>
<td>Position encoder</td>
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<tr>
<td>Operating mode</td>
<td>Deflection</td>
<td>Deflection accelerometer</td>
</tr>
<tr>
<td></td>
<td>Null</td>
<td>Servo-accelerometer</td>
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</table>

* Thermistor: a resistor whose resistance changes with temperature.
** Thermocouple: a temperature-sensing element which converts thermal energy directly into electrical energy.

Power Supply

- Modulating
  - Also known as Active Sensors
  - They need auxiliary power to perform functionality
  - Sensitivity can be controlled
- Self-Generating
  - Also known as Passive Sensors
  - They derive the power from the input

Operating Mode

- Deflection
  - The measured quantity produces a physical effect
  - Generates an apposing effect which can be measured
  - Faster
- Null
  - Applies the counter force
  - To balance the deflection from the null point (balance condition)
  - Can be more accurate but slow
Physical Property Being Measured

• Temperature
• Pressure
• Humidity
• Light
• Microphone (sound)
• Motion detector
• Chemical detector
• Image Sensor
• Flow and level sensor
• ...

Electrical Phenomena

• Resistive
• Capacitive
• Inductive
• Piezo-electric

Pressure Sensing: Principle and Types

• Transduces pressure into electrical quantity

• Pressure exerts force which can be converted to electrical voltage using various methods

• Types
  – Strain gauges
  – Capacitive diaphragms
  – Piezo-resistive or silicon cell
  – Bourdon tubes
  – Glass feed through with silicon cell
Pressure Sensor Types (1 of 2)

• Strain Gauges
  - Based on the variation of resistance of a conductor or semiconductor when applied to mechanical stress
  - Made of alloys like constantan, nichrome and also semiconductors
  - Can be bonded or un-bonded

• Capacitive diaphragms
  - Diaphragm acts as one plate of capacitor
  - The stress changes the space between capacitor plates
  - Can be made of strain gauge or other metal

Pressure Sensor Types (2 of 2)

• Piezo-resistive or Silicon Cell
  - Micro-machined silicon diaphragms
  - Piezo-resistive strain gauges diffused into it
  - Very sensitive to pressure

• Tubes and Feed-Through Glass
  - Glass feed through and silicon cell mounted on plastic housing
  - Based on the pressure difference

Humidity Sensing: Principle and Types

• Humidity is defined as the water vapor content in the air or other gases

• Measured as
  - Absolute Humidity
    • Ratio of the mass of water vapor to the volume of air or gas
  - Relative Humidity or RH
    • The ratio of the moisture content of air compared to the saturated moisture level at the same temperature or pressure
  - Dew Point
    • Temperature and pressure at which gas begins to condense into liquids
Humidity Sensor Types (1 of 2)

- **Capacitive RH sensor**
  - Change in dielectric constant is directly proportional to relative humidity in the environment
  - Very low temperature effect
  - 0.2-0.5 pF change in capacitance for 1% RH change

- **Resistive Humidity Sensors**
  - Measure the impedance change
  - Inverse exponential relationship to humidity
  - Mostly used are conductive polymer, salt etc.
  - Ceramic coated to avoid condensation effect

Humidity Sensor Types (2 of 2)

- **Thermal Conductivity** Humidity Sensors
  - Measure absolute humidity
  - Calculate the difference between dry air and air containing water vapor
  - One thermistor sealed in dry nitrogen and another exposed to environment
  - Difference in current proportional to humidity

- **MEMS-based** Humidity sensor
  - Polyimide-coated cantilever beam
  - Provided with movable electrode
  - Absorption causes increase in beam mass
  - Deflection causes capacitance change

Temperature Sensing: Principle & Types

- A temperature sensor detects a change in a physical parameter such as resistance or output voltage that corresponds to a temperature change.

  **Type of Sensing**
  - **Contact**
    - Sensor is in direct physical contact with the object to be sensed
    - To monitor solids, liquids, gases over wide range
  - **Non-contact**
    - Interprets the radiant energy of a heat source to energy in electromagnetic spectrum
    - Monitor non-reflective solids and liquids
Microphone Sensing: Principle

- A microphone is an acoustic to electric transducer that converts sound into an electrical signal.
- Microphones capture sound waves with a thin, flexible diaphragm. The vibrations of this element are then converted by various methods into an electrical signal that is an analog of the original sound.
- Most microphones in use today use electromagnetic generation (dynamic microphones), capacitance change (condenser microphones) or piezoelectric generation to produce the signal from mechanical vibration.

Condenser (or Capacitor) Microphones

- In a condenser microphone, the diaphragm acts as one plate of a capacitor, and the vibrations produce changes in the distance between the plates.
- Since the plates are biased with a fixed charge (Q), the voltage maintained across the capacitor plates changes with the vibrations in the air.

Dynamic Microphones

- In a dynamic microphone, a small movable induction coil, positioned in the magnetic field of a permanent magnet, is attached to the diaphragm.
- When sound enters through the windscreen of the microphone, the sound wave vibrations move the diaphragm.
- When the diaphragm vibrates, the coil moves in the magnetic field, producing a varying current in the coil through electromagnetic induction.
Accelerometer Sensor: MEMS

Types

- **Piezo-resistive**
  - Proof mass suspended with piezo-resistive beams.
  - Simple structure, fabrication, and readout (low imp. output).
  - Large temp. sensitivity, smaller overall sensitivity than capacitance devices.

- **Capacitive**
  - Acceleration is measured by the capacitance between a fixed plate and plate on the proof mass.
  - Stable (temperature, drift).
  - Can be susceptible to EMI.

Accelerometer: Inner Working (1 of 2)

It consists of beams and capacitive sensor with some anchor points.

On applying the acceleration, the beams deflect and cause the change in capacitance.
Motion Detector: Types

- **Photo Sensor**
  - Beam of light crossing the room near the door, and a photo sensor on the other side of the room. When the beam breaks, the photo sensor detects the change in the amount of light and rings a bell (garage doors).

- **Microwave- or Ultrasonic-based**
  - Burst of microwave radio energy and waits for the reflected energy to bounce back.
  - When a person moves into the field of microwave energy, it changes the amount of reflected energy or the time it takes for the reflection to arrive.
  - The same thing can be done with ultrasonic sound waves, bouncing them off a target and waiting for the echo.

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Pyro-electric Infrared Motion Detector

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Sensing Capabilities of Smartphones

- Embedded and pervasive computing platform
  - Does not run general-purpose programs
  - Have conventional interface
  - Persistent and ubiquitous device—must be pervasive
- Mobile Computing platform
  - Operates on the go
  - Adapts to available resources
- Wireless sensor platform
  - Contains an array of sensors
  - Context-aware
Evolution of the Mobile Phone

1983

- 30 minutes talk time
- Make calls

2011

- 13 hours talk time
- AMOLED touchscreen
- GPS, Wi-Fi, Bluetooth, USB
- 8 MP camera, 1080p video
- 1.4 GHz ARM CPU
- Sensors: accelerometer, gyro, proximity, compass, barometer

iPhone 4 - Sensors

- Accelerometer
- Magnetometer
- Gyroscope
- Light
- Proximity
- Camera
- Microphone
- Compass
- GPS

Smart Phone/Pad Sensors

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Nexus One</th>
<th>Nexus S</th>
<th>iPhone</th>
<th>Samsung Galaxy S</th>
<th>HTC Incredible</th>
<th>Galaxy Tab/Pad</th>
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<tr>
<td>Accelerometer</td>
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</tbody>
</table>
Accelerometer

• Measure the acceleration of the smartphone with a motion sensor that measures position with sound waves.
• The smartphone is at rest on the table.
• The accelerometer reading = ? (magnitude and direction)
• The acceleration measured by the motion sensor = ? (magnitude and direction)
Accelerometer

• Measure the acceleration of the smartphone with a motion sensor that measures position with sound waves.
• The smartphone is in free fall.
• The accelerometer reading = 0 (magnitude and direction)
• The acceleration measured by the motion sensor = g (down) (magnitude and direction)

Smartphones: MEMS Sensors

• Micro Electro-Mechanical Systems
• Term coined in 1989
• Describes creation of mechanical elements at a scale more usually reserved for microelectronics
• MEMS use cavities, channels, cantilevers, membranes, etc. to imitate traditional mechanical systems
• Small enough to be integrated with the electronics
MEMS Accelerometer

- Have a proof mass between springs and a series of ‘plates’
- Measure deflection via capacitance changes
- 1-D only

Gyroscope

- Angular velocity sensor
  - Coriolis effect – ‘fictitious force’ that acts upon a freely moving object as observed from a rotating frame of reference
1. Normally, a drive arm vibrates in a certain direction.
2. Direction of rotation
3. When the gyro is rotated, the Coriolis force acts on the drive arms, producing vertical vibration.
4. The stationary part bends due to vertical drive arm vibration, producing a sensing motion in the sensing arms.
5. The motion of a pair of sensing arms produces a potential difference from which angular velocity is sensed. The angular velocity is converted to, and output as, an electrical signal.

MEMS Gyroscope

• Based on measuring Coriolis force as experienced by a moving object in a rotating frame of reference
• Many implementations but the ‘tuning fork’ method is most common

Accelerometer vs. Gyroscope

• Accelerometer
  – Senses linear movement: not good for rotations, good for tilt detection
  – Does not know difference between gravity and linear movement
    • Shaking, jitter can be filtered out, but the delay is added
• Gyroscope
  – Measures all types of rotations
  – Not movement
  – Does not amplify hand jitter
• A+G = both rotation and movement tracking possible
Compass

- Magnetic field sensor (magnetometer)

MEMS Compass

- Most use Lorentz Force
- A current-carrying wire in a magnetic field experiences a perpendicular force

MEMS Barometer

- Resistance across membrane changes as it is stretched
Usage in Smartphones

- Accelerometers
  - Tilt estimation, orientation, shaking
- Gyroscopes
  - Smooth rotation tracking
- Magnetometers
  - Global orientation (maps)
- Barometer
  - GPS height hint
- Light sensor
  - Proximity Detection
- Camera
  - Imaging
- Microphone
  - Speech capture

Accessing Sensors (Android)

- We register for a particular sensor and provide a hint for the rate required

```java
public class SensorActivity extends Activity implements sensorEventListener {
    private SensorManager sensorManager;

    protected void onCreate(Bundle savedInstanceState) {
        super.onCreate(savedInstanceState);
        sensorManager = (SensorManager) getSystemService(SENSOR_SERVICE);
    }

    public void onSensorEventListener(SensorEvent event) {
        // Do something
    }
    public void onSensorEventListener(SensorManager, int id) {
        // Register specific sensor
    }
}
```

Continuous Sensing

- Most of the smartphone OSes assume you don’t want to register for 24/7 sensing events
- If you do, watch out that the OS doesn’t require some extra action on your part
  - e.g., some versions of Android put the CPU into a low power state after a certain time of screen inactivity.
  - The lowest power states preclude polling the sensor data...
- You might have to hold a wake lock on the CPU if you want to do this (which means the battery will deplete faster!)
Nominal Rates

- The sensor hardware samples at a constant (‘nominal’) rate but timestamping is error-prone
- Hence most smartphone APIs shy away from numerical rates. Android uses:

```java
case SENSOR_DELAY_FASTEST:
    delay = 0;
    break;
case SENSOR_DELAY_GAME:
    delay = 2000;
    break;
case SENSOR_DELAY_UI:
    delay = 66667;
    break;
case SENSOR_DELAY_NORMAL:
    delay = 200000;
    break;
```

Sampling

- Smartphone OSes are not real-time. Most sensors regularly update a register with values. The updates produce interrupts and eventually the OS gets around to collecting the value.
- If the OS is busy already, a new value could come in before we’ve read the last!
- Dropped readings...
- More recent sensors use a ring buffer so we don’t drop any, but...
- The timestamps are currently of the time the datum was collected and not the instant it was created...

Android Example

![Sensor Sampling Histogram on Android 2.3](image)
Sensor Filtering

• Warning: sometimes getting a higher sampling rate is pointless
• More and more sensors now have built-in low-pass filtering, which limits the max. frequency present. So high sampling rates might just result in oversampling!
• Normally not an issue (in fact a good thing) but wastes power and performance

Process Interference

• Sampling consistency can also be affected by high priority resource-intensive processes. In Android 2.3 the garbage collector ran with a higher priority than sensing...
• And other processes may request a higher rate for the same sensor at the same time! The logical thing is to run at the highest requested rate, but this might mean your app sees significant jumps in the rate of events.

Derived Sensors

• Initially the sensor access was raw, but now we have derived sensor types that fuse raw data to estimate other quantities. E.g., in Android:
  – TYPE_GRAVITY – Estimates the gravity vector by low pass filtering the accelerometers
  – TYPE_LINEAR_ACCELERATION – Estimates the acceleration having subtracted gravity
  – TYPE_ROTATION_VECTOR – Estimates the full rotational pose of the sensor in a world frame
• Specific implementation details vary (e.g. software/hardware, gyroscope for rotation or not)
• Can ignore and fuse ourselves of course...
Inertial Tracking

- It is very tempting to fuse the sensors together to track the phone’s trajectory → Inertial Measurement Unit
- Such tracking is relative. Errors accrue over time (so called ‘drift’)

Example: Linear Acceleration

- If the pose of the device is constant, double integrating the accelerometers after removing gravity should give displacement

\[ s = \int \int (a-g) \, dt \]

- However, bias introduces error that grows quadratically with time
- Double-integrating white noise produces a random walk
- End result is a fast (and unlimited) accrual of error

Example: Strapdown Navigation

- If the unit is additionally free to rotate, we need to map the phone axes to the world axes before we integrate. Strapdown navigation assumes the sensors are rigidly attached to the moving object (us)
- Requires the gyroscopes to track changes in axes as we move. But the gyroscopes give angular velocity: we must integrate to get angular change

\[ \Theta = \int g \, dt \]

- So now we integrate the gyro (linear error propagation) and then double integrate the accelerometers (quadratic), giving an error that grows as \( t^2 \)
Absolute Corrections

• To get something like this to work you must have periodic absolute positions/poses that allow you reset the error in the system
• Magnetometer will provide magnetic North provided we have a clean geomagnetic signal (not always the case indoors)
• GPS can give an absolute fix outdoors
• WiFi and 3G positioning might give us indoor fixes

Sensor Alignment

• It can be dangerous to assume the three sensors in a 3-D sensor are:
  – Perfectly orthogonal
  – Perfectly parallel to those of other sensors

Microphones in Smartphones

• Almost all new handsets use MEMS microphones (often plural!)
• Two conducting membranes, one on top of the other, acting as a capacitor
• Vibrations cause the capacitance to change
Frequency Response

Some Esoteric Applications

Cameras

• These vary, but more and more make use of MEMS for (auto)focus
• The underlying light sensor is no different from 'normal' cameras
• However the small, cheap lenses inevitably suffer from distortion
Distortion Correction

- Calibrate lens -> Remove distortion
- But this is a costly process

Camera Sensor

- With such small apertures, longer exposures are needed to get good output
- Hence phone cameras suffer from extensive noise in low light levels
  - Photon shot noise

Sensors: Where Next?

- MEMS sensors are getting cheaper and more capable – every new flagship phone seems to contain a new sensor; possibly even multiple sensors
- As programmers, look closely at the capabilities and remember:
  - model differences
  - instance differences
  - they’re never as good as you expect!
Pothole Patrol

- Acceleration data gathering from vehicles (geo-tagged)
- Simple data processing to detect a pothole, and statistical processing (clustering) for accurate detection

Community Awareness: Health and Wellness

- Personal environmental impact report (PIER) on “health and wellness”
- Participants use mobile phones to gather location data and web services to aggregate and interpret the assembled information (e.g., air pollution, CO2 emission, fast food exposure)

SoundSense

- Admission Control
- Acoustic Analysis
- Decision Tree Classifier
- Markov Model Recognizer
- Music Analysis
- Sound Detection Learning
Personal Sensing Applications

- Body Sensor Networks
  - Athletic Performance
  - Health Care
  - Activity Recognition

- Heart Rate Monitor
- Pulse Oximeter
- Mobile Phone Aggregator

Body Area Sensor Networks

- Portable
- Entirely user controlled
- Computationally lightweight
- Accurate

On-Body Sensors
- Sensing Accuracy
- Energy Efficiency

Phone
- User Interface
- Computational Power
- Additional Sensors

Opportunistic Personal Sensing Systems
### Participatory Public Sensing Systems

<table>
<thead>
<tr>
<th>Project</th>
<th>Sponsor</th>
<th>Participations</th>
<th>Description</th>
<th>Task</th>
<th>Operation</th>
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<tbody>
<tr>
<td>Example</td>
<td>UC</td>
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<td>Monitoring</td>
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</tbody>
</table>

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