CIS 607 Embedded Systems and Security

Sensors & Actuators

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Logistics

• One more paper added (TARDIS, Usenix Security’12)
  ‣ Anyone want to present?

• Final paper assignments today

• Project 1: set up Raspberry Pi
  ‣ 3 boards, make three groups
  ‣ Find documentation online and go through setup process
  ‣ Next week: discuss issues with setup and determine whether more/better documentation of process is necessary
Sensors and Actuators

Sensors:
- Cameras
- Accelerometers
- Rate gyros
- Strain gauges
- Microphones
- Magnetometers
- Radar/Lidar
- Chemical sensors
- Pressure sensors

Actuators:
- Motor controllers
- Solenoids
- LEDs, lasers
- LCD and plasma displays
- Loudspeakers

Modeling Issues:
- Physical dynamics
- Noise
- Bias
- Sampling
- Interactions
Magnetometers

A very common type is the Hall Effect magnetometer.

Charge particles (electrons, 1) flow through a conductor (2) serving as a Hall sensor. Magnets (3) induce a magnetic field (4) that causes the charged particles to accumulate on one side of the Hall sensor, inducing a measurable voltage difference from top to bottom.

The four drawings at the right illustrate electron paths under different current and magnetic field polarities.

Edwin Hall discovered this effect in 1879.
Accelerometers

Uses:
- Navigation
- Orientation
- Drop detection
- Image stabilization
- Airbag systems

The most common design measures the distance between a plate fixed to the platform and one attached by a spring and damper. The measurement is typically done by measuring capacitance.

Dragonboard has(?) accelerometer
By Newton’s second law, F=ma.

For example, F could be the Earth’s gravitational force.

The force is balanced by the restoring force of the spring.
Spring-Mass-Damper System

- mass: \( M \)
- spring constant: \( k \)
- spring rest position: \( p \)
- position of mass: \( x \)
- viscous damping constant: \( c \)

Force due to spring extension:
\[
F_1(t) = k(p - x(t))
\]

Force due to viscous damping:
\[
F_2(t) = -c\ddot{x}(t)
\]

Newton’s second law:
\[
F_1(t) + F_2(t) = M\ddot{x}(t)
\]
or
\[
M\ddot{x}(t) + c\dot{x}(t) + kx(t) = kp.
\]
Measuring tilt

Component of gravitational force in the direction of the accelerometer axis must equal the spring force:

\[ Mg \sin(\theta) = k(p - x(t)) \]

Given a measurement of \( x \), you can solve for \( \theta \), up to an ambiguity of \( \pi \).
Difficulties Using Accelerometers

- Separating tilt from acceleration
- Integrating twice to get position: Drift
- Vibration
- Nonlinearities in the spring or damper
The Berkeley Sensor and Actuator Center (BSAC) created the first silicon microaccelerometers, MEMS devices now used in airbag systems, computer games, disk drives (drop sensors), etc.

Gyroscopes

Optical gyros: Leverage the Sagnac effect, where a laser light is sent around a loop in opposite directions and the interference is measured. When the loop is rotating, the distance the light travels in one direction is smaller than the distance in the other. This shows up as a change in the interference.
Inertial Navigation Systems

Combinations of:

- GPS (for initialization and periodic correction).
- Three axis gyroscope measures orientation.
- Three axis accelerometer, double integrated for position after correction for orientation.

Typical drift for systems used in aircraft have to be:

- 0.6 nautical miles per hour
- Tenths of a degree per hour

Good enough? It depends on the application!
Water SCADA System

- Valve housing inside dam has microcontroller remote terminal unit (RTU) that controls actuation of the valve.
- Converts flow data into digital signals send over VHF to mill site where SCADA system sits.
Design Issues with Sensors

- **Calibration**
  - Relating measurements to the physical phenomenon
  - Can dramatically increase manufacturing costs

- **Nonlinearity**
  - Measurements may not be proportional to physical phenomenon
  - Correction may be required
  - Feedback can be used to keep operating point in the linear region

- **Sampling**
  - Aliasing
  - Missed events

- **Noise**
  - Analog signal conditioning
  - Digital filtering
  - Introduces latency
Aliasing

Sampled data is vulnerable to *aliasing*, where high frequency components masquerade as low frequency components.

A high frequency sinusoid sampled at a low rate looks just like a low frequency sinusoid.

Digitally sampled images are vulnerable to aliasing as well, where patterns and edges appear as a side effect of the sampling. Optical blurring of the image prior to sampling avoids aliasing, since blurring is spatial low-pass filtering.

Careful modeling of the signal sources and analog signal conditioning or digital oversampling are necessary to counter the effect.
Parseval's theorem relates the energy or the power in a signal in the time and frequency domains. For a finite energy signal $x$, the energy is

$$
\int_{-\infty}^{\infty} (x(t))^2 dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} |X(\omega)|^2 d\omega
$$

where $X$ is the Fourier transform. If there is a desired part $x_d$ and an undesired part (noise) $x_n$,

$$
x(t) = x_d(t) + x_n(t)
$$

then

$$
X(\omega) = X_d(\omega) + X_n(\omega)
$$

Suppose that $x_d$ is a narrowband signal and $x_n$ is a broadband signal. Then the signal to noise ratio (SNR) can be greatly improved with filtering.

Example:

$$
|X_d(\omega)|^2
$$

Filter:

$$
F(\omega)
$$

Filtered signal:

$$
|X_d(\omega) F(\omega)|^2
$$

A full treatment of this requires random processes.
bionicHand.jpg: Photo by Touch Bionics It’s got an embedded computer, a rechargeable battery, and five small dc motors. It costs US $18 500. And it can do things most other prosthetic hands just can’t, like grabbing a paper cup without crushing it, turning a key in a lock, and pressing buttons on a cellphone. The fingers of Touch Bionics’ iLIMB Hand are controlled by the nerve impulses of the user’s arm, and they operate independently, adapting to the shape of whatever they’re grasping. The hand can also do superhuman tricks, like holding a very hot plate or gripping an object tirelessly for days. A skin-tone covering gives the bionic hand a lifelike look, but some customers refer semitransparent models, to proudly flaunt their robotic hands. “They like the Terminator look,” says Touch Bionics CEO Stuart Mead. IEEE Spectrum, Oct. 2007.
Cameras

- Computer-controlled digital cameras
- Digital video cameras
- Specialized cameras
  - infrared
  - ultra fast/high resolution
  - motion trackers

*Pirates of the Caribbean: the Curse of the Black Pearl* (2003, Disney) pioneered the use of motion trackers coupled with computer-generated graphics.
Sensor Misuse

• Securing sensors is important, given how much information they can glean
  ‣ spiPhone: use accelerometer as keystroke dynamics tool, figure out passwords from keyboard
  ‣ PlaceRaider: reconstruct full model of room from composite of images made by camera
  ‣ SCADA.... ?