Week 4: Mechatronics

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Announcements

• Continue to bring your laptop and power cord (and USB converter, if needed) to class for the rest of the quarter.

• If you need to adjust the mechanics of your Hapkit, please do this before Thursday.

• Try to get checked off on Lab 4 by the end of class Thursday.

• Note: No Thursday office hours due to Alumni lecture.
Hapkit Sensor

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sensor types

• magnetic
  magnetic: TrakStar, Ascension

• optical
  optical: Polaris, NDI

• acoustic
  optical: Microsoft Kinect
  acoustic: ultrasonic proximity sensor, BiF

• inertial
  inertial: wearable IMU, MotionNode

• **mechanical**
  (our focus, since these are the sensors typically integrated with the actuator in kinesthetic haptic devices)

• mechanical
  mechanical: Faro arm
mechanical trackers

- ground-based linkages most commonly used
- joint position sensors
  - digital: optical encoders are most common
  - analog: magnetic sensors and potentiometers are most common
Encoders

• how do they work?
  – Typically, a focused beam of light aimed at a matched photodetector is interrupted periodically by a coded pattern on a disk
  – In our case, the rotation is sensed by magnetic signals instead of light
  – Produces a number of pulses per revolution (Lots of pulses = high cost)

• quantization problems at low speeds

• absolute vs. referential
Encoders

- phase-quadrature encoder
  - 2 channels, 90° out of phase
    - allows sensing of direction of rotation
    - 4-fold increase in resolution
Hall-Effect Sensors

How do they work?

a small transverse voltage is generated across a current-carrying conductor in the presence of a magnetic field

(Discovery made in 1879, but not useful until the advent of semiconductor technology.)
Hall-Effect Sensors

\[ V_h = \frac{R_h IB}{t} \]

- amount of voltage output related to the strength of magnetic field passing through.
- linear over small range of motion (need to be calibrated)
- affected by temperature, other magnetic objects in the environments

\[ V_h = \text{Hall voltage} \]
\[ R_h = \text{Hall coefficient} \]
\[ I = \text{Current} \]
\[ B = \text{Magnetic flux density} \]
\[ t = \text{Element thickness} \]
measuring velocity

• differentiate position
  – advantage: use same sensor as position sensor
  – disadvantage: get noisy signal

• alternative
  – for encoders, measure time between ticks
discrete differentiation

• many different methods

• simple example:
  – average 20 readings = $P_1$
  – average next 20 readings = $P_2$
  – where $t$ is the period of the servo loop

\[ V = \frac{P_1 - P_2}{t} \]

• differentiation increases noise

• usually need to filter
Hapkit Actuator

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Actuator types

For kinesthetic haptic devices, the actuator of choice is the electric motor, specifically:

- DC (direct current)
- Brushed
- PM (permanent magnet)
PM DC brushed motors

• Rotating *armature* with coil windings is caused to rotate relative to a permanent magnet

• Current is transmitted through brushes to armature, and is constantly switched so that the armature magnetic field remains fixed.
DC motor components
DC motor terms

• Cogging/torque ripple
  - tendency for torque output to ripple as the brushes transfer power

• Friction/damping
  - caused by bearings, brushes, and eddy currents

• Stall torque
  - max torque delivered by motor when operated continuously without cooling
Torque ripple

http://www.maxonmotorusa.com/
Motor equations

- Torque constant
  \[ \tau = k_T i \]
- Speed constant
  \[ v_{emf} = k_v \dot{q} \]

- Dynamic equations
  \[ v = L \frac{di}{dt} + Ri + v_{emf} \]
  \[ m \ddot{q} + b \dot{q} = \tau \]
Motor amplifier types

**current amplifier**
(voltage controlled current source VCCS)

- directly controls current
- current = torque (good!)
- expensive

**voltage amplifier**
(voltage controlled voltage source VCVS)

- indirectly controls current
- current depends on several factors
- less expensive

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Circuit board design by Louis Whitcomb, JHU

ardumotor shield (https://www.sparkfun.com/products/9815) and Adafruit TB6612 1.2A DC/Stepper Motor Driver Breakout Board
Pulse width modulation

assumes that the average signal is a constant signal

duty cycle is the proportion of on time to the period

useful if you do not have a D/A converter to send analog signals to the motor circuit

switching frequency must be much faster than the mechanical dynamics of the system

http://www.barrgroup.com/
Motor in your Hapkit

Pololu MP 12V Motor

https://www.pololu.com/product/3236/specs
Transmission

• Transfers/amplifies force/torque from motor

• You don’t want to feel or see the effects of the transmission!

• Types:
  – gears
  – belts/pulleys
  – capstan drive
  – none (direct drive)
Capstan drive

high transmitted force, low transmitted friction
Many haptic applications, such as the rendering of virtual environments with damping (in which force is proportional to velocity), require velocity measurement. Velocity is typically obtained by numerical differentiation of the position signal obtained by an encoder. An algorithm for velocity estimation must be selected which is free of noise but minimizes phase lag at the frequencies of interest [30, 36]. Thus, an alternative method is to use specialized hardware that measures the time between encoder ticks in order to compute the velocity [30, 37].

**Force Sensors**

Force sensors are used in haptic devices as the operator input to an admittance-controlled device, or as a mechanism for canceling device friction and other undesirable dynamic properties in an impedance-controlled device. Force sensors are described in Sect. 20.4. When a force sensor such as a strain gauge or load cell measures the operator's applied force, care must be taken to thermally isolate the sensor, since thermal gradients in the sensor caused by body heat can affect force readings.

### 30.2.3 Actuation and Transmission

Haptic devices are differentiated from traditional computer input devices by actuators that are controlled to provide appropriate haptic sensations to the human operator. The performance of the haptic device depends heavily on the actuator properties and the mechanical transmission between the actuator and the haptic interaction point (HIP).

**Requirements for Haptics**

The primary requirements for actuators and mechanical transmission in impedance-type haptic devices are: low inertia, low friction, low torque ripple, back-driveability, and low backlash. In addition, if the design is such that the actuator itself moves as the user's position changes, a higher power-to-weight ratio is desired. Although closed-loop force control has been used for haptic display in impedance devices, most often the mechanism is designed to have sufficiently low friction and inertia so that open-loop force control is accurate enough.

One common mechanical transmission for haptic devices is the capstan drive (Fig. 30.6), which consists of smooth cables wrapped around pulleys of differing diameter to provide a gear ratio. A no-slip, high-friction contact between the cable and the pulleys is maintained through several wraps of the cable. The capstan drive minimizes friction forces felt by human operator cause it prevents translational forces on motor and joint axes.

Current amplifiers are typically used to create a direct relationship between the voltage output by the computer via a digital-to-analog (D/A) converter and the torque output by the motor. The effect of actuator and amplifier dynamics and D/A resolution on system stability is typically negligible in comparison to position sensor resolution and sampling rate for most haptic devices. Actuator or amplifier saturation can produce undesirable behavior, particularly in multi-degree-of-freedom haptic devices where a single saturated motor torque may change the apparent geometry of virtual objects. The force vector, and thus the corresponding actuator torques, must be scaled appropriately if any actuator is saturated.

### 30.2.4 An Example Device

As an illustrative example, we will provide detailed design information for a simple one-degree-of-freedom haptic device known as the Haptic Paddle [30, 38]. This section is meant to provide a concrete description of the types of components that are used in kinesthetic haptic devices, and the device can also be constructed following the instructions provided by John Hopkins University [30, 39]. Many widely available haptic devices share the common working principles of this device and differ chiefly in kinematic details arising from a greater number of degrees of freedom.
Direct drive

motors attached directly to link(s)

Hayward (McGill)