Controller Design and Tuning

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A control system (or "controller") is a system whose purpose is to command, direct, or regulate itself, or another system. The System under Control is often called a "plant" (as in "chemical production plant"). There are open-loop and closed-loop control systems.

Closed-loop control system: e.g., human picking an object
- Eyes are sensors.
- Hands are actuators.
- Brain is the controller that estimates the distance between hand and object based on sensor input. It determines/computes an appropriate control action that satisfies requirements and implements it through the actuators.

Open-loop control system: e.g., blindfolded picking
- Only the current state and a model of the plant are used. The output of the system under control is not observed.

Our example (closed loop): velocity control in rail car
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Moving Car (the physical “plant”) Model

\[ F_{res} = F_{traction} + F_{drag} \]

\[ F_{drag} = -\frac{1}{2} \cdot p \cdot v^2 \cdot C_D \cdot A \]

\[ F_{res} = M \cdot a = M \cdot \frac{dv}{dt} \]

\[ \frac{dv}{dt} = \frac{1}{M} \left( F_{traction} - \frac{1}{2} \cdot p \cdot v^2 \cdot C_D \cdot A \right) \]

\[ v(0) = 0 \]
PID Controller

A Proportional-Integral-Derivative (PID) controller takes as input the error (deviation of the measured/sensed value from the ideal or “setpoint” value) $v_i - v$ and produces an output to be sent to the plant via the actuator.
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- **Proportional Controller** – outputs $K_p \cdot (v_i - v)$, with $K_p$ an appropriate constant;
- **Integral Controller** – outputs $K_i \cdot \int (v_i - v) dt$, with $K_i$ an appropriate constant;
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**Derivative Controller** – outputs $K_d \cdot \frac{d(v_i - v)}{dt}$, with $K_d$ an appropriate constant;
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A PID controller produces a control output:

$$K_p \cdot (v_i - v) + K_i \cdot \int (v_i - v)\,dt + K_d \cdot \frac{d(v_i - v)}{dt}$$
Closed-Loop PID Controller for Velocity Control

Environment (e.g., slope profile)

F_traction

plant (rail car)

controller

v

v_i
Rail Car Case

Build the controller for a driverless rail car. The controller determines the acceleration of the train, in an attempt to match (i.e., deviate as little as possible from) a predefined profile of desired velocities. The desired (piecewise constant) velocity profile is known beforehand by a central coordinator (and is encoded in a file). Passengers should not fall (i.e., accelerate too much). Other requirements such as minimizing total energy consumption could be added.
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Abstracting the Passenger: Mass-Spring-Damper System

\[
\begin{align*}
F_{\text{ext}} &= -f \\
F_{\text{spring}} &= -k(-x) \\
F_{\text{damper}} &= -c(-v) \\
M \cdot a &= F_{\text{ext}} + F_{\text{spring}} + F_{\text{damper}} \\
\frac{dv}{dt} &= a \\
\frac{dx}{dt} &= v
\end{align*}
\]
Abstracting Train-and-Passenger ("Plant" model)

\[
\begin{align*}
  m_{\text{passger}} \cdot a_{\text{passger}} &= k(-x_{\text{passger}}) + c(-v_{\text{passger}}) - m_{\text{passger}} \cdot a_{\text{train}} \\
  F_{\text{traction}} &= (m_{\text{train}} + m_{\text{passger}}) \cdot a_{\text{train}} \\
  a_{\text{passger}} &= \frac{dv_{\text{passger}}}{dt} \\
  v_{\text{passger}} &= \frac{dx_{\text{passger}}}{dt} \\
  a_{\text{train}} &= \frac{dv_{\text{train}}}{dt} \\
  v_{\text{train}} &= \frac{dx_{\text{train}}}{dt}
\end{align*}
\]
Some Results - Train Velocity

\[\begin{align*}
    m_{\text{passger}} &= 73kg \\
    m_{\text{train}} &= 6000kg \\
    k &= 300 \\
    c &= 150 \\
    K_p &= 100 \\
    K_i &= 0 \\
    K_d &= 0
\end{align*}\]
Some Results - Passenger Displacement and Acceleration
Some Results - Train Velocity

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\begin{align*}
    m_{\text{passger}} &= 73\text{kg} \\
    m_{\text{train}} &= 6000\text{kg} \\
    k &= 300 \\
    c &= 150 \\
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    K_i &= 0 \\
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\end{align*}
\]
Some Results - Passenger Displacement and Acceleration

People displacement and train acceleration (200, 0, 0)
Some Results - Train Velocity

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\begin{align*}
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    m_{\text{train}} & = 6000\text{kg} \\
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    c & = 150 \\
    K_p & = 200 \\
    K_i & = 10 \\
    K_d & = 0
\end{align*}
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