Plan of the Lecture

- Today's topic: what is feedback control? past, present, future

Goal: get comfortable with the idea of *feedback control* as a means of getting *unreliable* or *unstable components* to behave *reliably*.

Recommended reading:

- FPE, Chap. 1 — some historical background
- K.J. Åström and P.R. Kumar, "Control: a perspective," to appear in Automatica, 2014

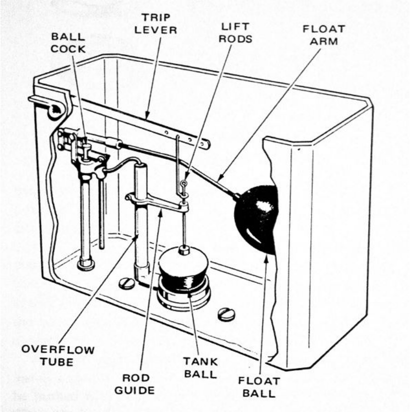
Control All Around Us: The Thermostat

Honeywell T-86 “Round”
Thermostat (1953)

Nest 2nd Gen Learning
Thermostat (2014)

The thermostat maintains desired (reference) temperature despite disturbances (such as doors opening/closing, variations of outside temperature, number of persons in the house, etc.)

Control All Around Us: The Toilet Tank



The flush toilet employs a control mechanism that ensures that the toilet gets flushed and that the tank is filled to a set reference level. Similar systems are used in other applications where fluid levels need to be regulated.

Components of a Control System

Some terminology:

- the plant is the system being controlled
- the sensors measure the quantity that is subject to control
- the actuators act on the plant
- the controller processes the sensor signals and drives the actuators
- the control law is the rule for mapping sensor signals to actuator signals

Feedback Control: Some History

1788: James Watt patents the centrifugal governor for controlling the speed of a steam engine. The governor combines sensing, actuation, and control.

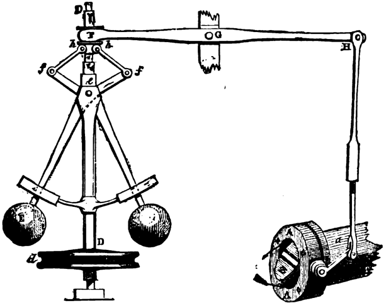


FIG. 4.—*Governor and Throttle-Valve.*

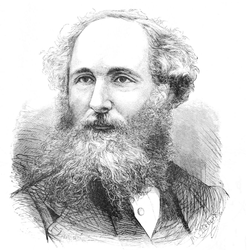
The original governor kept the engine running at (more or less) constant speed via what is known today as proportional control. Many improvements were added to the original design.

Feedback Control: Some History

1868: James Clerk Maxwell publishes the first theoretical study of steam engine governors. By that time, there were more than 75,000 governors installed in England.

J.C. Maxwell, "On governors," Proc. Royal Society, no. 100, 1868

... [Stability of the governor] is mathematically equivalent to the condition that all the possible roots, and all the possible parts of the impossible roots, of a certain equation shall be negative. ...
I have not been able completely to determine these conditions for equations of a higher degree than the third; but I hope that the subject will obtain the attention of mathematicians.



The general stability criterion was found in 1876 by Edward John Routh and, in an equivalent form, independently by Adolf Hurwitz in 1895. We will study their criterion in ECE 486.

Feedback Control: Some History

Ever since the invention of the centrifugal governor, control attracted the interest of engineers, mathematicians, physicists, economists ...

In Russia, Ivan Vyshnegradsky developed stability criteria of steam engine governors in 1876, independently of Maxwell. He was a director of St. Petersburg Technological Institute (1875–1878), and ended his career as a Minister of Finance of the Russian Empire (1887–1892).

Some of the earliest textbooks on control:

- M. Tolle, *Die Regelung der Kraftmaschinen*, Berlin, 1905.
- N.E. Joukowski, *The Theory of Regulating the Motion of Machines*, Moscow, 1909.

Industrial Process Control

Early development of controllers was driven by engineering rather than theory. The effects of integral and derivative action were rediscovered by tinkering.

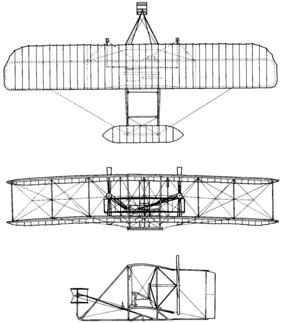
Some interesting facts:

- By mid-1930's, there were more than 600 control companies in the U.S.
- In 1931, Foxboro developed the Stabilog — the first general-purpose proportional-integral-derivative (PID) controller, with adjustable gains from 0.7 to 100
- Between 1925 and 1935, about 75,000 controllers were sold in the U.S.

– K.J. Åström and P.R. Kumar, "Control: a perspective," to appear in Automatica, 2014

Insights from Flight Control

1905: Orville and Wilbur Wright made the first successful experiment with manned flight.



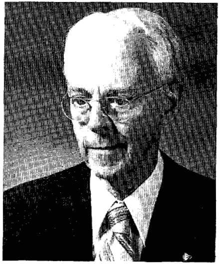
Their main insight was that the airplane itself had to be inherently unstable, which would give the pilot more control and render the overall flying system (pilot and machine) stable.

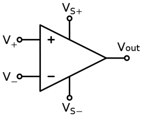
The first autopilot was developed by Sperry Corp. in 1912.

The Benefits of Negative Feedback: The Op Amp

1927: Harold S. Black of Bell Labs developed negative feedback amplifier to reduce signal distortion in long-distance telephony.

I suddenly realized that if I fed the amplifier output back to the input, in reverse phase, and kept the device from oscillating ..., I would have exactly what I wanted: a means of canceling out the distortion in the output. ... By building an amplifier whose gain is deliberately made ... higher than necessary and then feeding the output back on the input in such a way as to throw away the excess gain, it had been found possible to effect extraordinary improvement in constancy of amplification and freedom from non-linearity.





Curious fact: it took nine years (!) for Black's patent to be granted because the patent officers refused to believe that the amplifier could work.

Control at Bell Labs: Frequency-Domain Methods

The invention of the op amp spurred on further developments in the theory and practice of feedback control:

- 1932 — Harry Nyquist studied how sinusoidal signals propagate around the control loop and developed the Nyquist stability criterion
- 1934 — Hendrik Bode studied the relationship between attenuation and phase (leading to the concepts of phase and gain margins); identified fundamental limitations of feedback control (Bode's sensitivity theorem); and developed graphical methods (Bode plots) for designing feedback controllers (loop shaping)

We will cover this material in the 2nd half of the semester.

Feedback Control after 1940

Further developments in control systems were a direct result of World War II ...

- fire control (anti-aircraft, ships, automated aiming ...)
- ballistics and guidance systems (autopilot, gyro compass ...)

... and the Cold War:

- unmanned and manned space flight
- control with humans in the loop (Norbert Wiener's cybernetics)
- communication networks ...

The aerospace industry was at the forefront of control technology because of extreme demands for safety and performance. It was one of the early adopters of state-space methods, e.g., the use of Kalman filter for navigation in the Apollo Project.

Control: The Hidden Technology

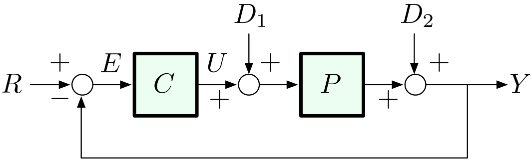
These days, control systems are everywhere:

- home comfort (Roomba, thermostats, smart homes, ...)
- communication networks (routing, congestion control, ...)
- automotive and aerospace industry (safety-critical systems, autopilots, cruise control, autonomous vehicles, ...)
- biology and medicine (cardiac assist devices, anesthesia delivery, systems biology ...)
- the arts (▸ dynamic works of Raffaello D'Andrea)

... but the basic analysis and design techniques are still the same as in the early days:

- block diagrams (flow of information)
- Laplace transforms and transfer functions
- graphical techniques: root locus, Bode and Nyquist plots
- state-space methods (linear algebra)

Feedback Control in Five Minutes



Systems:

C – controller

(or compensator)

P – plant

Variables:

R – reference

E – error

D_1, D_2 – disturbances

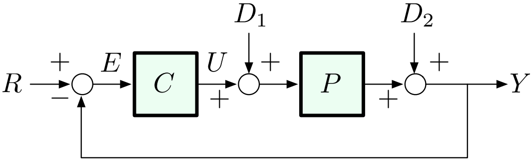
U – control (or input)

Y – output

Key relations:

$$Y = D_2 + P(U + D_1) \quad U = CE \quad E = R - Y$$

Feedback Control in Five Minutes



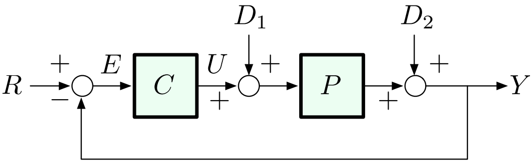
$$Y = D_2 + P(U + D_1) \quad U = CE \quad E = R - Y$$

Let's express Y in terms of R, D_1, D_2:

$$\begin{aligned} Y &= D_2 + P(CE + D_1) \\ &= D_2 + P\Big(C(R - Y) + D_1\Big) \qquad \text{negative feedback!!} \\ &= D_2 + PCR - PCY + PD_1 \end{aligned}$$

$$Y = \frac{PC}{1 + PC} R + \frac{P}{1 + PC} D_1 + \frac{1}{1 + PC} D_2$$

Feedback Control in Five Minutes



$$Y = \frac{PC}{1+PC}R + \frac{P}{1+PC}D_1 + \frac{1}{1+PC}D_2$$

Suppose C is a large positive *gain*. What happens as $C \to \infty$?

$$\frac{PC}{1+PC}R \xrightarrow{C\to\infty} R \qquad \text{reference tracking}$$

$$\frac{P}{1+PC}D_1 + \frac{1}{1+PC}D_2 \xrightarrow{C\to\infty} 0 \qquad \text{disturbance rejection}$$

Bottom line: in the limit $C \to \infty$, $Y = R$

(this "Big Picture" is too good to be true — we will fill in all the details!!)

For the Next Few Lectures ...

... start reviewing:

- complex numbers
- differential equations
- Laplace transforms