EE3: Introduction to Electrical Engineering

Lecture 5: Automatic Control

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Outline

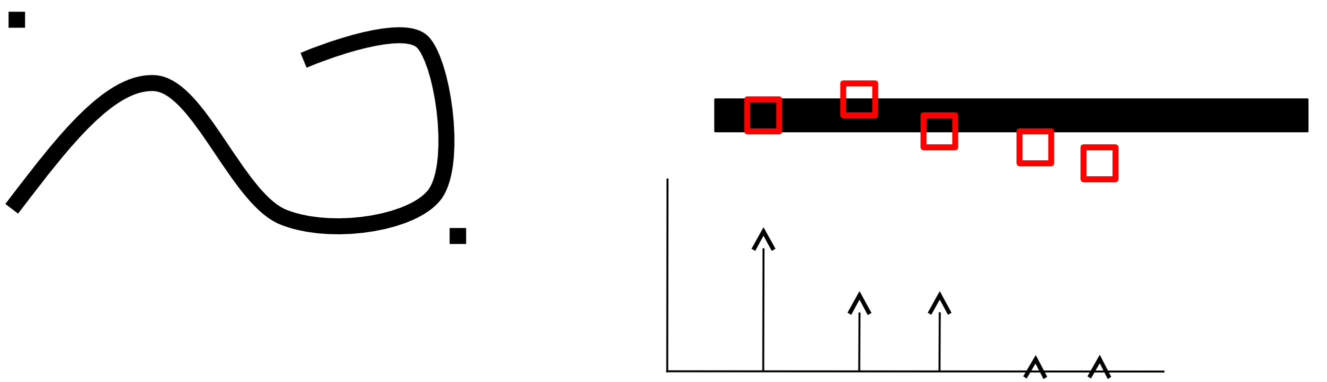
- Industrial control applications
- Feedback principle
- Analog controllers
- Digital approach

Industrial Control

- Motor speed
- Machine position and pose
- Industrial process
- Network stability
- Electronics gradually replaced mechanical controllers and humans in the loop
- Digital ICs now dominate

Example

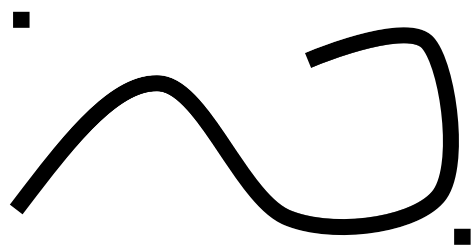
A robot is to follow a line on the ground. It is equipped with a sensor that produces a high voltage when it is above the line, that linearly declines as the robot moves off the line until it is zero.



How should we command the robot to move based on the sensor readings?

Open Loop Control Approach

If we know the equation of the line, and how the robot moves in response to commands, we could pre-compute the set of actions the motor will take. This has several problems

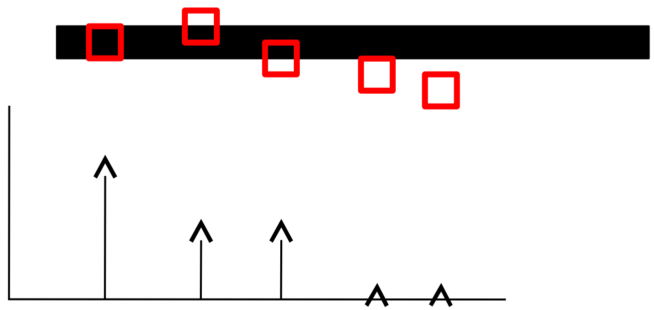


1. It can be computationally difficult

2. It is subject to model errors: must precisely calibrate motions over the surface of interest.

3. It will accumulate errors and eventually diverge from the path. However, this sometimes is good enough.

Feedback Control Approach



If the voltage is high, proceed in same direction

If the voltage has dropped, and previously had been going straight or right, turn a little to the left; else if it is dropping, and had turned left, turn a little to the right

If the voltage is increasing, turn a little more in the same direction.

If the voltage is zero, turn back with a larger turn.

Feedback Control Approach II

The relation between the feedback signal and the control action taken is called the control law

By far the most popular laws are based on linear approximations: when the controller is close to the optimal solution, the error is approximately linearly related to the correction signal required.

The example however is non-linear with respect to a single sample, because we don't know the correct sign to use in the correction

This forces "dithering" in the controller: make small experimental motions, remember the result, and use this in conjunction with derivative of voltage to determine the next motion.

Aside: Taylor's Incredibly Useful Theorem

For any function *f(x)* with continuous second derivative,

$$f(x^*+h) = f(x^*) + \frac{df(x^*)}{dx}h + \frac{1}{2}\frac{d^2 f(\xi)}{dx^2}h^2$$

$$\text{where } x^* < \xi < x^*+h$$

Put another way, we can approximate the function in the region of x^* by the linear function

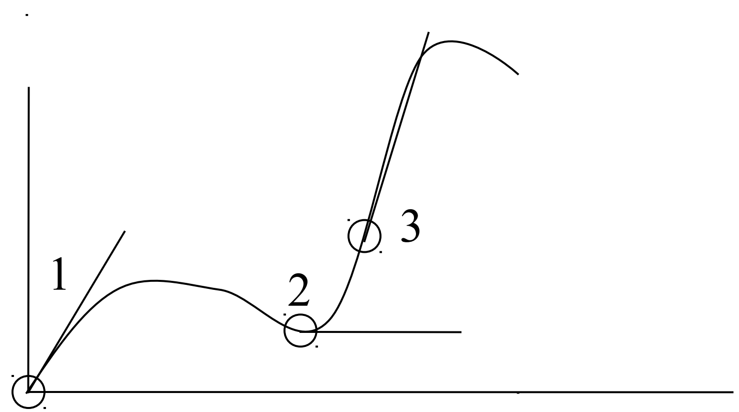
$$g(y) = a + mh \text{ where } a = f(x^*),\ m = \frac{df(x^*)}{dx},\ y = x^*+h$$

The error is bounded by the maximum size of the second derivative, and is quadratic in the offset *h*; for small *h* the error is thus very low. This is the main justification for the use of linear models; the other is that linear models are computationally easy to use.

Example: Taylor's Theorem

$$f(x^*+h) = f(x^*) + \frac{df(x^*)}{dx}h + \frac{1}{2}\frac{d^2 f(\xi)}{dx^2}h^2$$

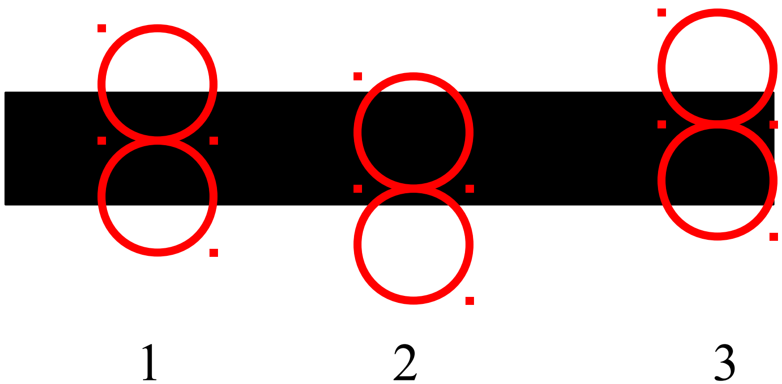
$$\text{where} \; x^* < \xi < x^*+h$$

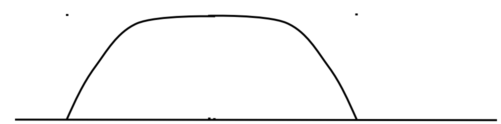


The range under which the approximation is good depends on the size of the second derivative. In the above it is worst at 2, while at 3 the function is nearly linear. When model error is large, the controller must make more frequent small adjustments.

Improved Feedback Control

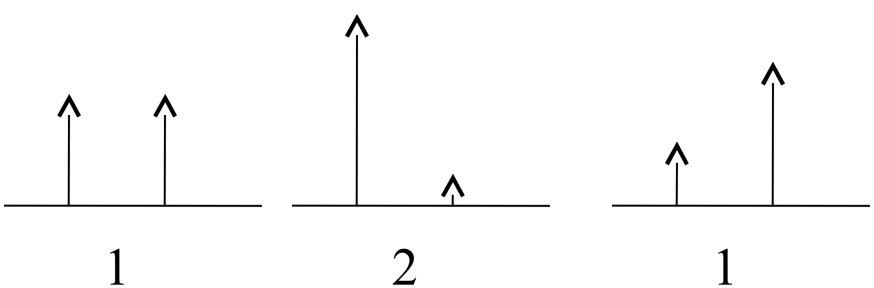
Consider now that we have two sensors, as illustrated.





Response as crosses line

The individual sensor response is much less useful than the difference signal between two sensors:



Rule: turn towards the high signal. When near center, the problem is almost linear; turn angle can be proportional to difference.

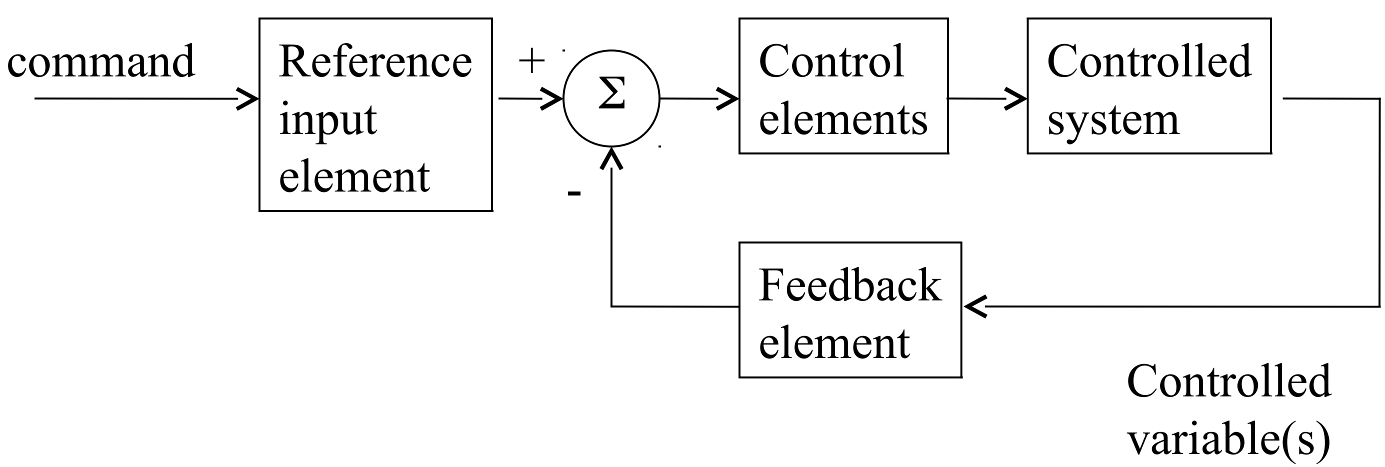
EFTS

Suppose we try to follow the line $f(x)=4-x^2$. If we can execute course corrections of at most 5 degrees every 0.1 s, what is the maximum speed we can travel? Hint: begin by finding the point of maximum curvature, and then look at the difference between the linear approximation and the actual function.

Solution: The maximum curvature occurs for $x=0$, for which the linear approximation is the line $y=4$. In 0.1 s, we travel $0.1v$, where v is the velocity. We require $(4-f(0.1v))/(.1v)<5/360$. For example, if $v=1$ m/s, we get .01/.1=.1>0.014; at 0.1 m/s we get 0.01<0.014. The answer is 0.14 m/s.

Servomechanism

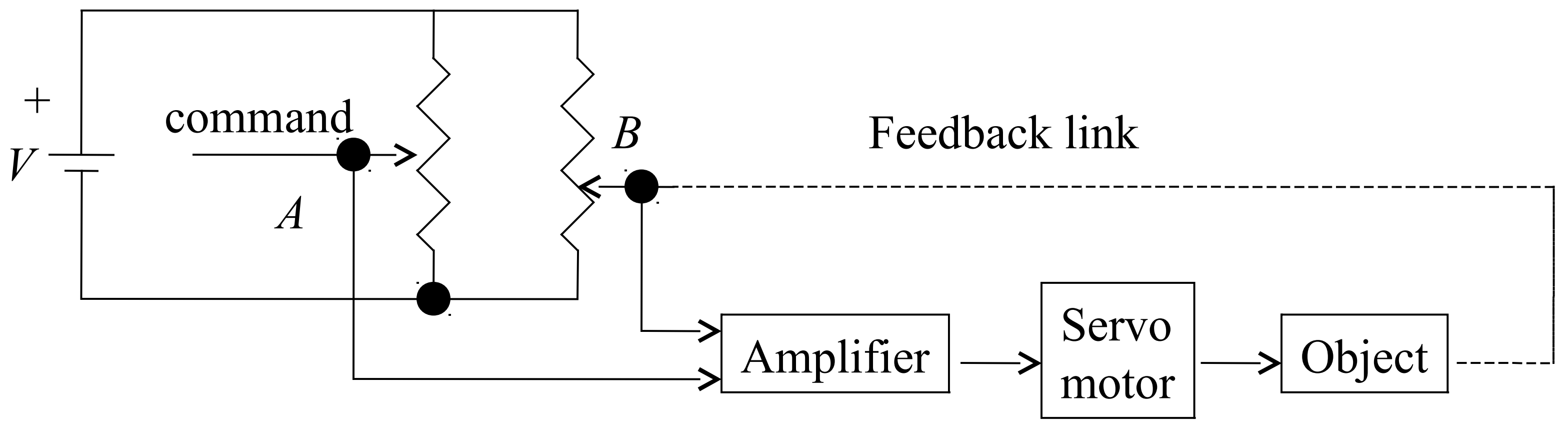
Any feedback controller that controls position, velocity or acceleration is called a servomechanism. Servo motors are the combination of a motor and this type of controller. The general form of the control system is as follows.



Implicitly, there is a model of the system to be controlled. Feedback reduces the required accuracy of the model and measurements, when near control target.

Servomechanism Example

The branch marked *A* in the potentiometer determines the desired location of a platform. The branch marked *B* has a mechanical connection that produces a voltage proportional to position



On a disturbance or control input, a difference signal results. This drives a control action (amplified voltage to motor) that brings the object back to the desired position.

The correction signal gets smaller as it approaches.

EFTS

For the preceding servomechanism example, what factors affect how quickly the platform would move to the commanded position?

Solution: Every block matters, as follows

1. Difference in voltage in the potentiometer (related to initial difference in position)
2. Amplification, which affects size of control signal to motor
3. Torque/control signal relation for motor
4. Mass of platform, since work must be done by the motor.

There may also be deliberate smoothing introduced to limit peak accelerations (why is this usually needed?)

PID Controllers

A common approach used to produce smooth control actions for processes described by differential equations is called proportional-integral-derivative (PID) control.

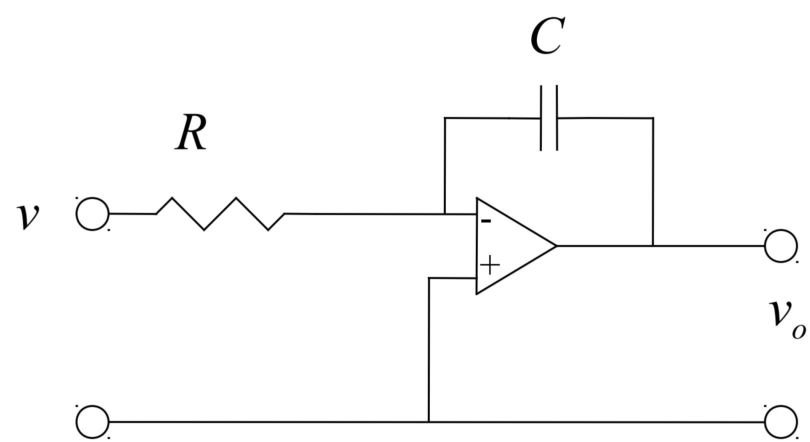
Let e(t) be the error signal. Then the control sign

$$u(t) = K_P e(t) + K_I \int_{-\infty}^{t} e(t)dt + K_D \frac{de(t)}{dt}$$

Action directly on the error is designed to reduce it (e.g., by moving in direction opposite its sign), action on the integral is intended to reduce steady state error, while action on the derivative can help to avoid overshoots in response to transients.

This was classically implemented using op amps.

Analog Integration



As usual, no current flows into the op amp.

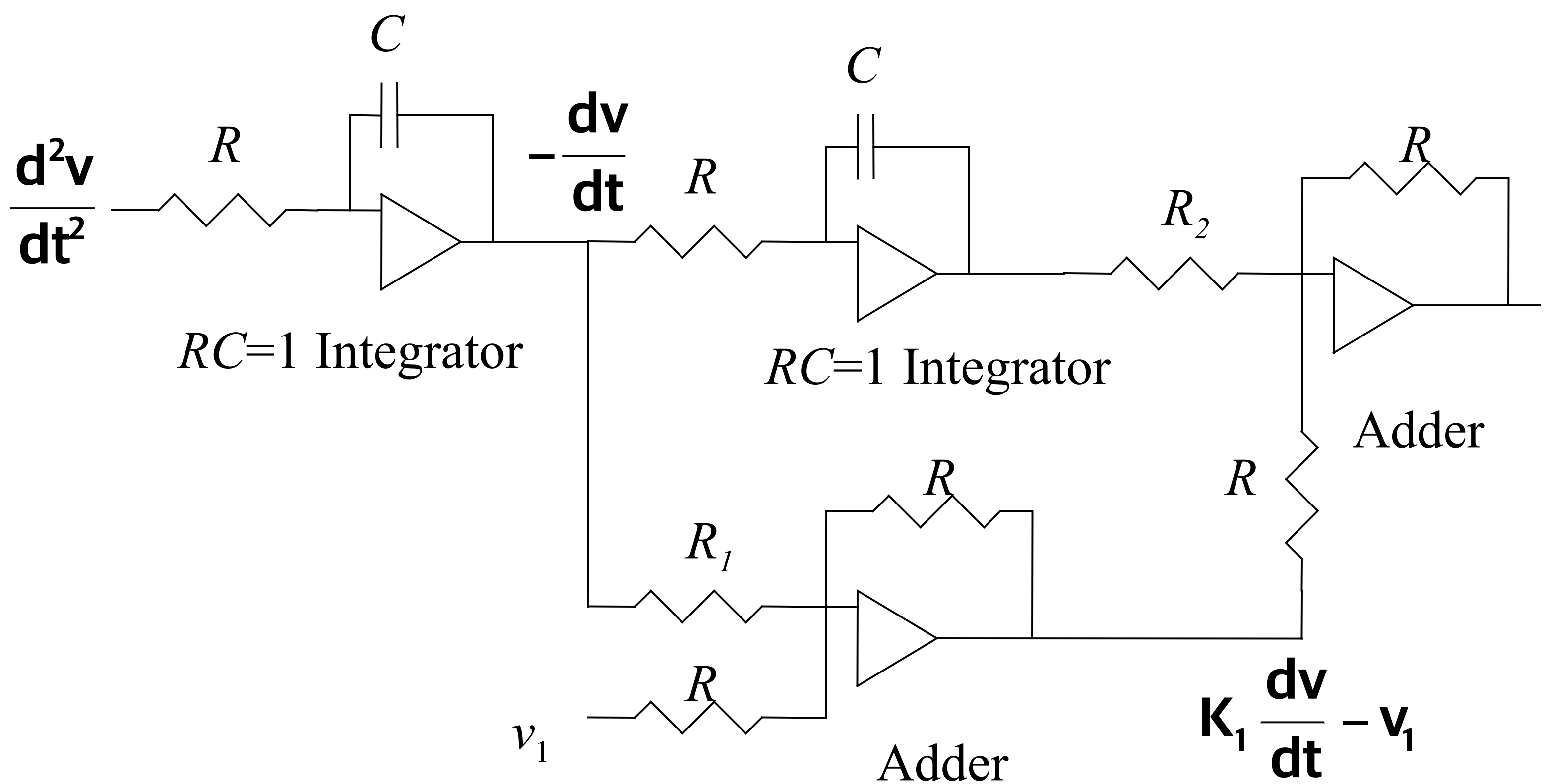
Moreover the -ve input is a virtual ground so t

$$i = v/R,\ v_0 = \frac{1}{C}\int i dt = -\frac{1}{RC}\int v dt$$

Differentiators are less stable, and so differential equations are generally re-written in terms only of derivatives; then integrators and adders enable the solution.

Example

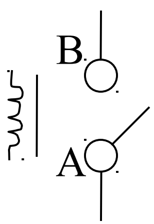
Program the differential equation $\frac{d^2v}{dt^2} + K_1\frac{dv}{dt} + K_2 v - v_1 = 0$



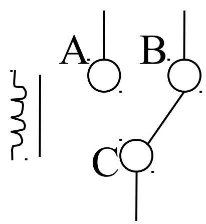
Switches and voltage sources across the capacitors and a switch at the v_1 input allow setting of initial conditions.

Digital Ladder Logic

The earliest electronic digital logic used in controllers was based on relays. It was common in early computers, railway control systems, telecommunications crossbar switches, and devices such as elevators.



Single throw relay



Double throw relay

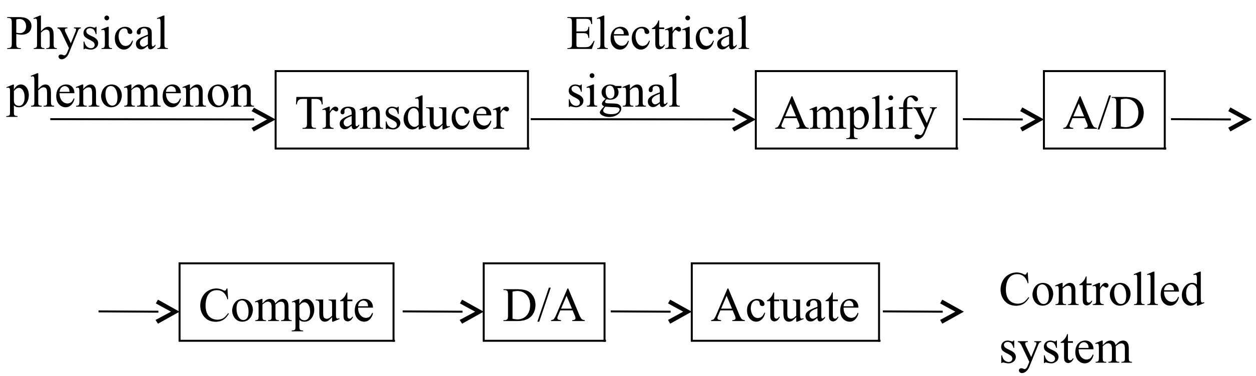
AND (voltage high if all inputs high, low otherwise)—connect normally open relays in series

OR (voltage high if any input high, low otherwise)—connect normally open relays in parallel

NAND, NOR: use normally closed circuits in series, parallel

Modern Digital Control

The typical configuration used from sensing to control action within the feedback loop is shown below



Transducer: a sensor; e.g., a microphone takes pressure waves and generates a current or voltage

A/D: three steps; filter, sample, quantize

D/A: puts a staircase function through a low pass filter

Modern Digital Control II

Relay logic did not require A/D and was highly reliable. Why was it eventually abandoned?

1. As IC's became more highly integrated, their size and cost went down enormously.

2. Microcontrollers can be easily re-tasked, to deal with new models or produce more complex control behaviors (including non-linear situations)

Analog computers based on op amps were competitive as recently as 1970 in simulating physical systems described by differential equations; but for similar reasons they were replaced by digital computers.

Summary

- Open loop control often demands unreasonable accuracy
  - Physical model
  - Precision of measurement and movement
- Closed loop (feedback) control relaxes requirements
  - Usually linear model, for low computation
  - Small errors are suppressed by sequence of control actions
- Evolution from analog to digital control
  - Original controllers were mechanical (e.g., speed governor)
  - Relays and op amps followed, together with formal control theory
  - Now mainly digital, due to Moore's Law.