An Outline of Control Systems Design

Feedback Control of Dynamic System, Prentice Hall

The aim of the process is to aid the product or the process, the mechanism, the robot, the chemical plant, the aircraft, etc.

Sequence of Characteristic Steps

- Understand the process and translate dynamic performance requirements into time, frequency, or pole-zero specifications.
- Select sensors.
- Select actuators.
- Make a linear model.
- Try a simple proportional-integral-derivative (PID) or lead-lag design.
- Evaluate/modify plant.
- Try an optimal design.
- Build a computer model and simulate the performance of the design.
- Build a prototype and test it. If not satis2fied, return to step 1 and repeat.

Understand the process

- What it is intended to do?
- How much system error is permissible?
- How to describe the class of command and disturbance signals to be expected.
- Use the simplified model for its intended purpose (linear, time invariant transfer function), and to return to an accurate model or the actual physical system to really verify the design performance.

Sensors

- Consider which variables are important to control and which can physically be measured.
- Some factors that influence sensor selection:

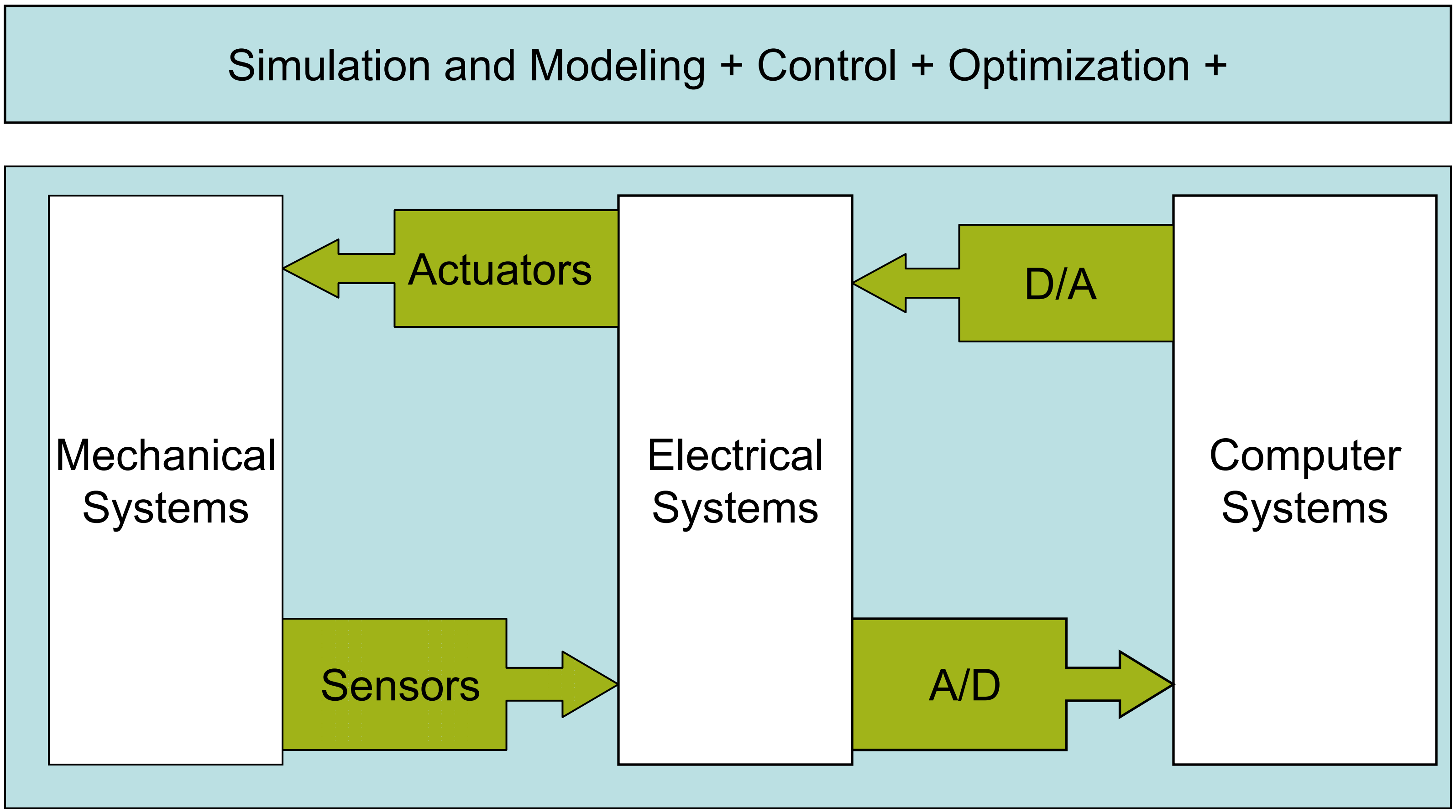
  - **Number of sensors and location:** minimum number and their optimal location.
  - **Technology:** Electric or magnetic, mechanical, electromechanical, piezoelectric.
  - **Performance:** Linearity, bias, accuracy, bandwidth, resolution, dynamic rang, noise.
  - **Physical properties:** Weight, size, strength.
  - **Quality factor:** Reliability, durability, maintainability.
  - **Cost:** Expense, availability, facilities for test and maintenance.

Actuators

- In order to control a dynamic system, you must be able to influence the response. The device that does this is the actuator.
- Before choosing a specific actuator, consider which variables can be influenced.

- Some factors that influence sensor selection:
  - Number of actuators and locations.
  - **Technology:** Electric, hydraulic, pneumatic, thermal, etc.
  - **Performance:** Maximum force possible, extend of the linear range, maximum speed possible, power, efficiency.
  - **Physical properties:** Weight, size, strength.
  - **Quality factors:** Reliability, durability, maintainability.
  - **Cost:** Expense, availability, facilities for testing and maintenance.

System Main Elements

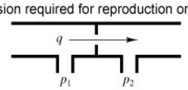


Electromechanical Real Time Interfacing

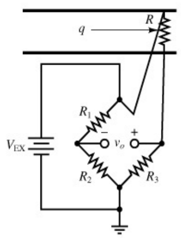
Sensors: Signal Classification

Sensor design always involves the application of some law or principle of physics or chemistry that relates the quantity of interest to some measurement event.

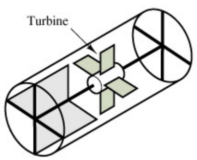
- **Motion, position and dimensional variable:**
  - *Potentiometers; stress and strain gages; capacitive sensors; differential transformers, optical sensors.*
- **Force, torque, pressure and flow:**
  - *Strain gages; piezoelectric sensors; capacitive sensors.*
- **Flow:**
  - *Turbine meters; electromagnetic sensors; imaging sensors.*
- **Temperature:**
  - *Thermocouples; thermometers.*
- **Liquid level:**
  - *Motion transducers; Force transducers.*
- **Humidity:** *Semiconductor sensors and MEMS.*
- **Chemical composition:** *Gas analysis equipment; semiconductor gas sensors.*



Differential-pressure flowmeter: A calibrated orifice and a pair of pressure transducers permit the measurement of flow rate.
(a)



Hot-wire anemometer: A heated wire is cooled by the gas flow. The resistance of the wire changes with temperature.
(b)



Turbine flowmeter: Fluid flow induces rotation of the turbine; measurement of turbine velocity provides an indication of flow rate.
(c)

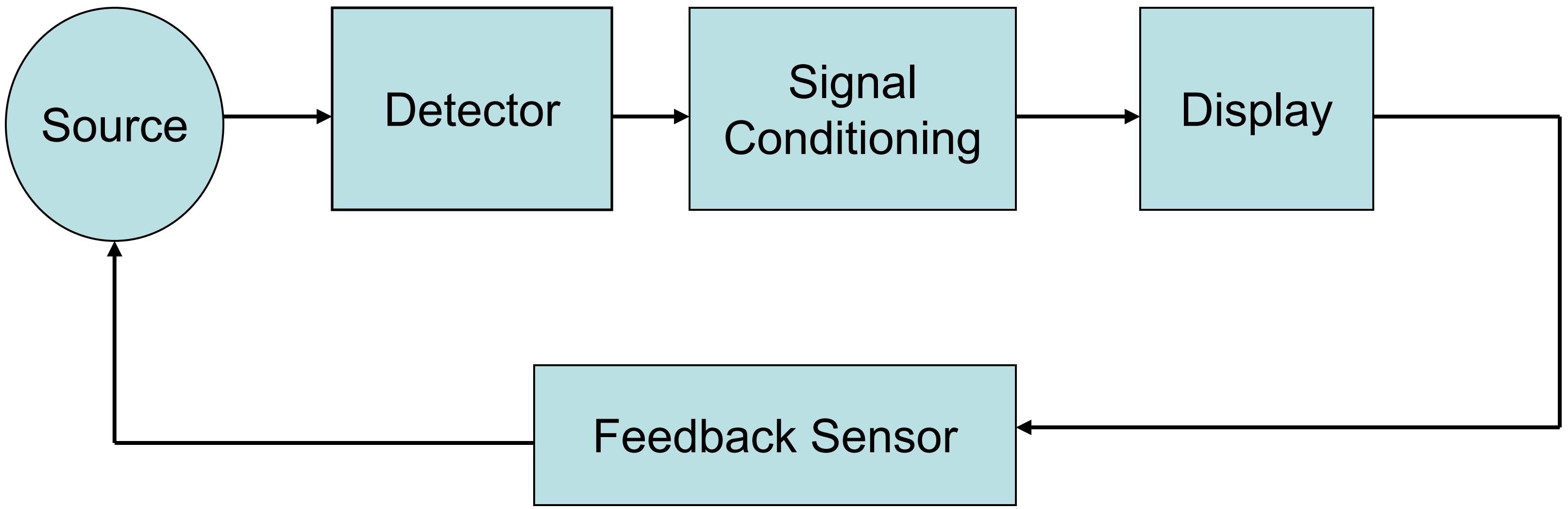
Instrumentation: Sensors and Transducers

- An important component in systems that is linked to instrumentation is the sensor, whose function is to provide a mechanism for collecting information about a particular process.

- Sensors transform real-world data into electrical signals. The sensor may be defined as a device that produces an output signal for the purpose of sensing of a physical phenomenon. Sensors are also referred as transducers.

- The extent to which sensors and transducers are used depends upon the level of automation and the complexity of the control system. There is always a need for faster, sensitive, and precise measuring devices, accordingly, sensors are being miniaturized in solid state form by combing several sensors and signal processing mechanisms.

Sensor-Based Measurement System

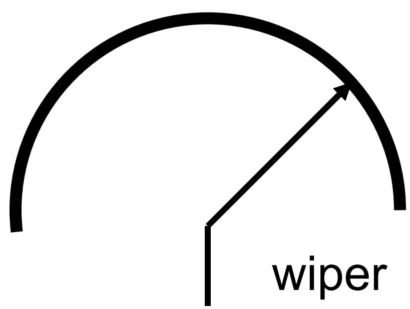


Types of Sensors

- **Active Sensors:** They require external power for their operation.
- **Passive Sensors:** Examples include piezoelectric, thermoelectric, and radioactive.
- **Analog Sensors:** They have an output that is proportional to the variable being measured.
- **Digital Sensors:** They are accurate and precision.
- **Deflection Sensors:** They are used in a physical setup where the output is proportional to the measured quantity that is displayed.
- **Null Sensors:** In this type, any deflection due to the measured quantity is balanced by the opposing calibrated force so that any imbalance is detected.

Resistance Transducers

- A displacement transducer that uses the variable resistance transduction principle may be manufactured with a **rotary** or **linear** potentiometer (rotation or displacement is converted into a potential difference).
- Such potentiometers consist of a wiper that makes contact with a resistive element, and as this point of contact moves, the resistance between the wiper and end leads of the device changes in proportion to the angular displacement.
- Through voltage division, the change in resistance can be used to create an output voltage that is directly proportional to the input displacement.



Inductance Transducers

- Inductance transducers are used for proximity sensing when the presence or absence of an object must be detected with an electronic non-contact sensor. They are also used for motion position detection, motion control, and process control applications.
- Variable inductance transducers are based on Faraday's law of induction in a coil: the induced voltage is equal to the rate at which the magnetic flux through the circuit changes

$$V = N\frac{d\phi}{dt} = N\frac{d(BA)}{dt} = \frac{dN(\phi)}{dt} = \frac{d\varphi}{dt}$$

(ψ is the total flux linkage in the circuit)

$$L = \frac{\psi}{i} = \frac{N\phi}{i}$$

$$\phi = \frac{Ni}{R}$$

$$L = \frac{N^2}{R}; R = \frac{1}{\mu A} = N^2\mu\left(\frac{A}{l}\right)$$

Capacitance Transducers

- The variation in capacitance between two separated members or electrodes is used for the measurement of many physical phenomena.
- A change in capacitance can be brought about by varying any one of the three parameters
  - Distance between the two electrodes
  - Changing the dielectric constant
  - Changing the area of the electrodes
- Variable capacitance transducers have applications in the area of liquid level measurements in chemical plants

$$C = \frac{\varepsilon A}{d}$$

$$\frac{\Delta C}{C} = -\frac{\Delta d}{d}$$

$$\frac{\Delta C}{C} = \frac{\Delta A}{A}$$

Wheatstone Bridge

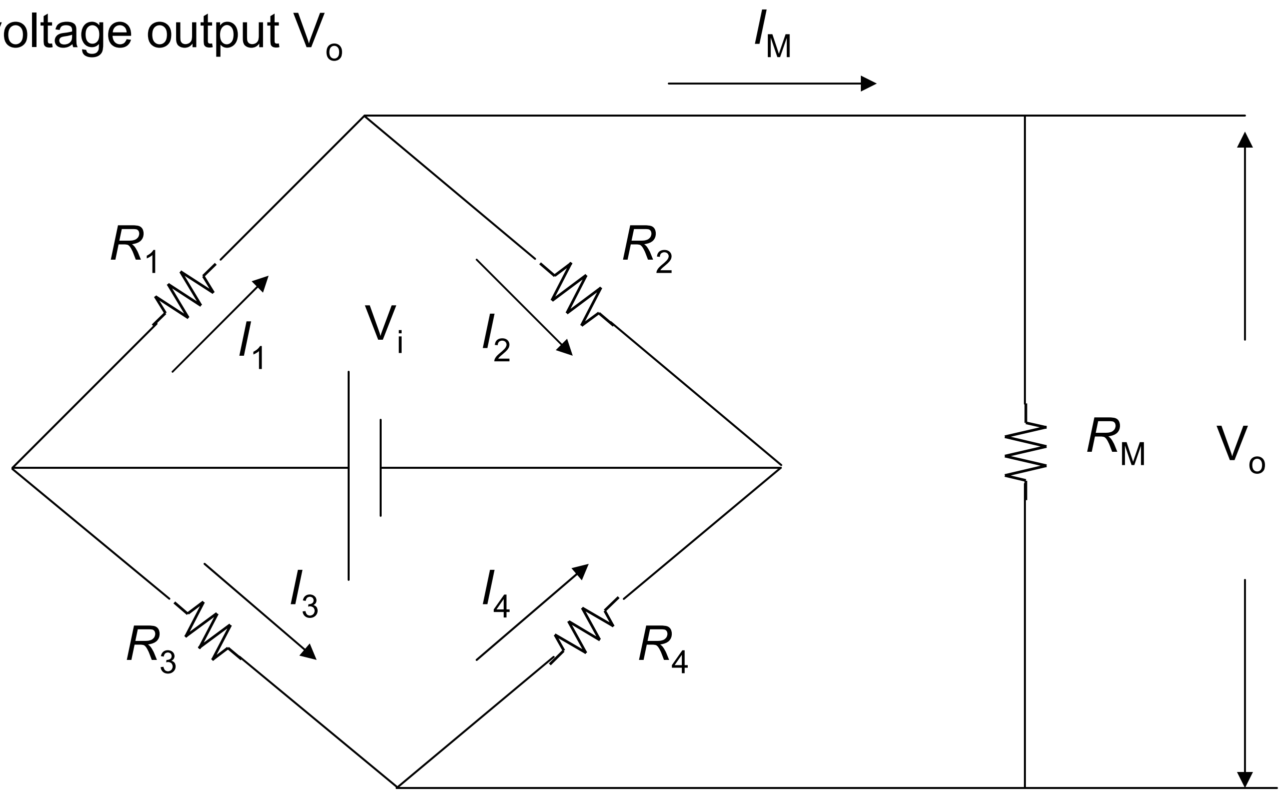
- The bridge converts a relative change of resistance $\delta = \Delta R/R$ into a proportional voltage output V_o

$$I_1R_1 - I_3R_3 = 0$$

$$I_2R_2 - I_4R_4 = 0$$

$$\frac{I_1R_1}{I_2R_2} = \frac{I_3R_3}{I_4R_4}$$

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$



Piezoelectric Strain Sensors

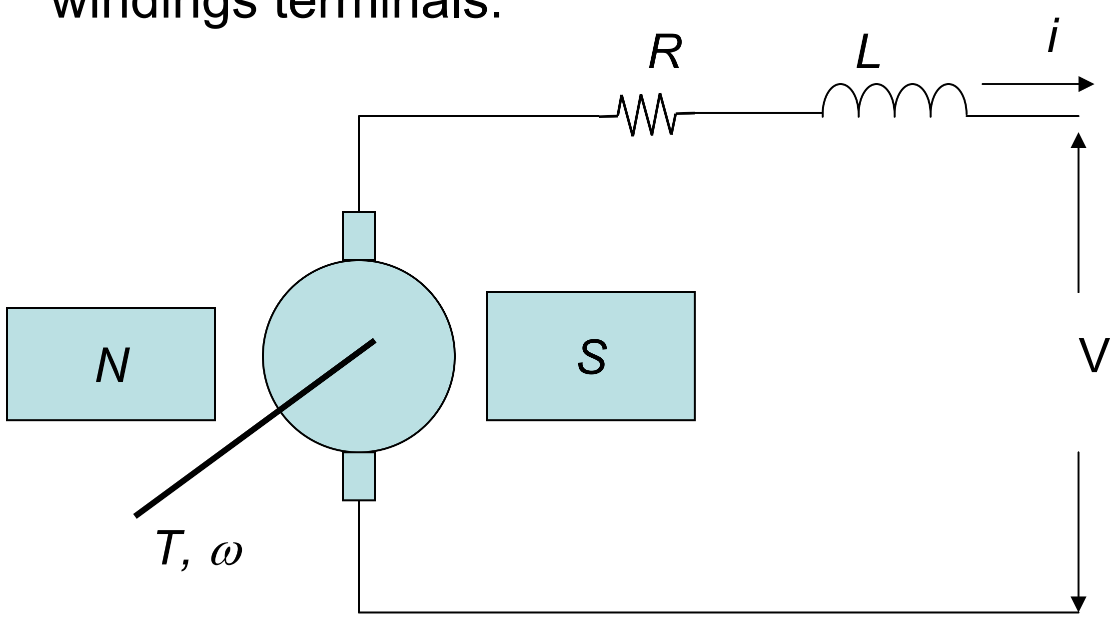
- The piezoelectric effect consists of generating an electric charge when a material is subject to a mechanical deformation or in producing a mechanical deformation when it is subject to an electric charge. The piezoelectric effect, in piezoelectric materials, can be induced by applying a high electric field while the material is heated above a specific temperature called Curie temperature.
- The strain transducers can also be used to measure indirectly force, torque, pressure, velocity, or acceleration.
- The main parameters of a piezoelectric sensor are: Curie temperature (^{o}C), dielectric constant c (F/m), Young or elastic modulus E (N/m^2), piezoelectric charge coefficient, d_{ij} (C/N), and piezoelectric voltage coefficient, g_{ij} (Vm/N). The first subscript (i) indicates the direction perpendicular to the electrodes, and the second subscript (j) indicates the direction of the applied stress.

$$d_{ij} = \frac{\text{Charge density produced in direction i}(\text{C/m}^2)}{\text{mechanical stress applied in direction j}(\text{N/m}^2)}$$

$$g_{ij} = \frac{\text{Charge density produced in direction i}(\text{V/m})}{\text{mechanical stress applied in direction j}(\text{N/m})}$$

Velocity Measurement: Tachometer

- A permanent magnet DC generator can be used for analog measurement of angular velocity. ω is the angular velocity to be measured, T is the torque required to drive the generator, L and R are the inductance and the capacitance of the rotor, I is the current in the rotor windings, and V is the voltage output at the rotor windings terminals.



Actuators
Relays and Motors

- DC Motors
  - Permanent magnet
  - Series wound
  - Shunt wound
  - Separately excited
  - Compound wound

Torque-speed characteristic; speed control; reversible; regenerative breaking

- AC Motors
  - Single phase
    - Squirrel cage
    - Wound rotor
  - Three phase
    - Induction
    - Synchronous
  - Universal motors

Linear Models

- Construct a small-signal dynamic model valid over the range of frequencies included in the specifications.

- Validate the model with experimental data where possible.

- Express the model in state-variable and pole-zero form as well as in frequency response form.

- Use MATLAB or other simulation tools to simulate the system.

- Simplify and reduce the order of the model if necessary.

- Quantify model uncertainty.

Controllers

- To form an initial estimate of the complexity of the design problem, sketch its frequency response (Bode plot) and a root locus with respect to plant gain.

- If the plant-actuator-sensor model is stable and minimum phase, the Bode plot will probably be the most useful, otherwise, the root locus shows very important information with respect to behavior in the right-hand plane.

- Try to meet the specifications with a simple lead-lag variety including integral control if steady-state error response requires it.
- Do not look feed forward of the disturbances if the necessary sensor information is available.

- Consider the effect of sensor noise, and compare a lead network to a direct sensor of velocity to see which gives a better design.

Evaluation/Plant Modification

- Evaluate the source of the undesirable characteristics of the system performance.

- Reevaluate the specifications, the physical configuration of the process, and the actuator and sensor selections in light of the preliminary design, and return to step one if improvement seems necessary or feasible.

- It is necessary to consider all parts of the design, not only the control logic, to meet the specifications in the most-cost effective way.

Try an Optimum Design

- If the trial and error compensators do not give satisfactory performance, consider a design based on optimal control.
- The root locus will show possible root locations from which to select locations for the control poles that meet the response specifications.
- You can select locations for the estimator poles that represent a compromise between sensor and process noise.
- Plot the corresponding open-loop frequency response and the root locus to evaluate the stability margins of this design and its robustness to parameter changes. You van modify the pole locations until a best compromise results.

Simulation

- After reaching the best compromise among process modification, actuator and sensor selection, and controller design choice, run a computer model of the system.
- This model should include important nonlinearities, such as actuator saturation, realistic noise sources, and parameter variations you expect to find during operation of the system.
- It is also possible to compute a digital equivalent of the analog controller.
- The results of the simulation prove the design satisfactory.

Prototype

- Before production, it is common to build and test a prototype. At this point you verify the quality of the model, discover unsuspected vibration and other modes and consider ways to improve the design.

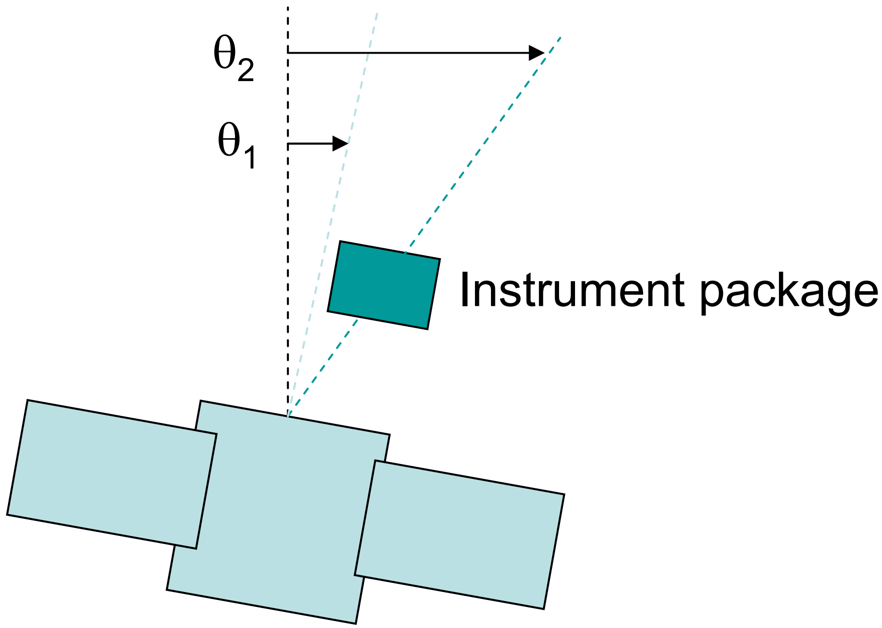
- Implement the controller using embedded software/hardware.

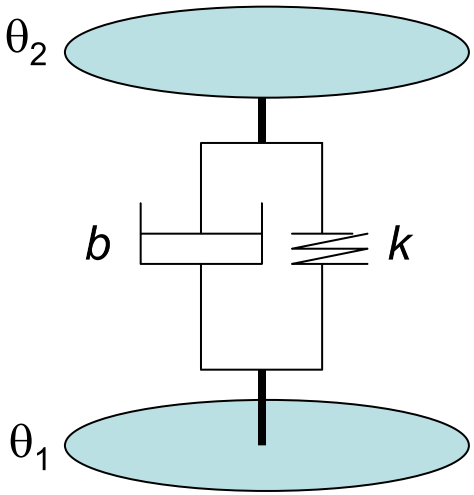
- Tune the controller if necessary.

- After these tests, you may want to reconsider the sensor, and process and return to step 1.

Case Study

Design of a Satellite’s Attitude Control (Angular Orientation)





- Attitude is in effect, the way that the object is "pointed.“

- In order for the ship to go in the right direction, attitude must be monitored and controlled. If even a tiny mistake in the way the ship is pointed is not corrected, the ship can end up millions of miles.

- The attitude is continuously controlled by a programmed control loop: sensors measure the satellite's attitude, the onboard computer then processes these measurements and generates commands which are carried out by the actuator, to ensure correct pointing.

Understand the process and its performance specifications

- We model the spaceship as two masses connected by a flexible boom.
- θ_2 is the angle between the star sensor and the instrument package.
- θ_1 is the angle of the main satellite with respect to the star.
- Disturbance torques due to solar pressure and orbit perturbations are ignored.
- The pointing requirement arises when it is necessary to point the unit in another direction. It can be met by dynamics with a transient settling time of 20 seconds and an overshoot of no more than 15%.
- The dynamics of the satellite include parameters that can vary.
- The control must be satisfactory for any parameter values in a pre-specified range to be given when the equations are written.

Select Sensors

- In order to orient the package, it is necessary to measure the attitude angles of the package.
- For this reason, a **star tracker** may be proposed.
- The star tracker is a system based on gathering an image of a specific star and keeping it centered on the focal plane of the telescope. This is usually a small (1 inch) telescope mounted at a fixed angle to a rotating bearing. A photocell or solid-state camera arrangement sees the star. There are 57 bright navigational stars in common use. One of the most commonly used is Sirius (the brightest).
- This sensor gives a relatively noisy but very accurate reading proportional to θ_2, the angle of deviation of the instrument package from the desired angle.
- To stabilize the control, a rate gyro is included to give a clean reading of $\dot{\theta}_2$ because a lead network on the star-tracker signal would amplify the noise too much.

Select Actuators

- Major considerations in selecting the actuator are precision, reliability, weight, power requirements, and lifetime.
- Alternatives for applying torque are: cold-gas jets, reaction wheels or gyros, magnetic torquers, and gravity gradients.
- The jets have the most power and are the least accurate.
- Reaction wheels are precise but can transfer on momentum, so jets or magnetic torques are required to dump momentum from time to time.
- Magnetic torquers provide relatively low levels of torque and are suitable only for some-altitude satellite missions.
- A gravity gradients also provides a very small torque that limits the speed of response and places severe restrictions on the shape of the satellite.

Make a Linear Model

$$J_1\ddot{\theta}_1 + b(\dot{\theta}_1 - \dot{\theta}_2) + k(\theta_1 - \theta_2) = T_c$$

$$J_2\ddot{\theta}_2 + b(\dot{\theta}_2 - \dot{\theta}_1) + k(\theta_2 - \theta_1) = 0$$

where T_c is the control torque on the main body. With

$$J_1 = 1 \text{ and } J_2 = 0.1$$

$$G(s) = \frac{10bs + 10k}{s^2(s^2 + 11bs + 11k)}$$

$$\mathbf{x} = [\theta_2 \quad \dot{\theta}_2 \quad \theta_1 \quad \dot{\theta}_1]^T$$

$$
\dot{\mathrm{x}} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\dfrac{k}{j2} & -\dfrac{b}{j2} & \dfrac{k}{j2} & \dfrac{b}{j2} \\ \dfrac{k}{j1} & \dfrac{b}{j1} & -\dfrac{k}{j1} & -\dfrac{b}{j1} \\ & & & \end{bmatrix} \mathbf{x} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \dfrac{1}{J_1} \end{bmatrix} u
$$

$$
y = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} \mathrm{x}
$$

- Physical analysis of the boom leads us to assume that the parameters k and b vary as a result of temperature fluctuations but are bounded by $0.09 \leq k \leq 0.4$ and $0.038\ (k/10)^{1/2} \leq b \leq 0.2\ (k/10)^{1/2}$.
- Accordingly the vehicle's natural resonance frequency ω_n can vary between 1 and 2 rad/s, and the damping ratio varies between 0.02 and 0.1.
- One approach to control design when parameters are subject to variations is to select nominal values for the parameters.
- Construct the design for this model and then test the controller performance with other parameter values.
- For this case you may choose ω_n =1 and the damping ratio as 0.02.
- With values k = 0.091, b = 0.0036, J_1 = 1 and J_2 = 0.1, the nominal equations become

$$\dot{\mathrm{x}} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -0.91 & -0.036 & 0.91 & 0.036 \\ 0 & 0 & 0 & 0 \\ 0.091 & 0.0036 & -0.091 & -0.0036 \end{bmatrix} \mathbf{x} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} u$$

$$y = [1 \quad 0 \quad 0 \quad 0\,]\mathrm{x}$$

$$G(s) = \frac{0.036(s+25)}{s^2(s^2+0.04s+1)}$$

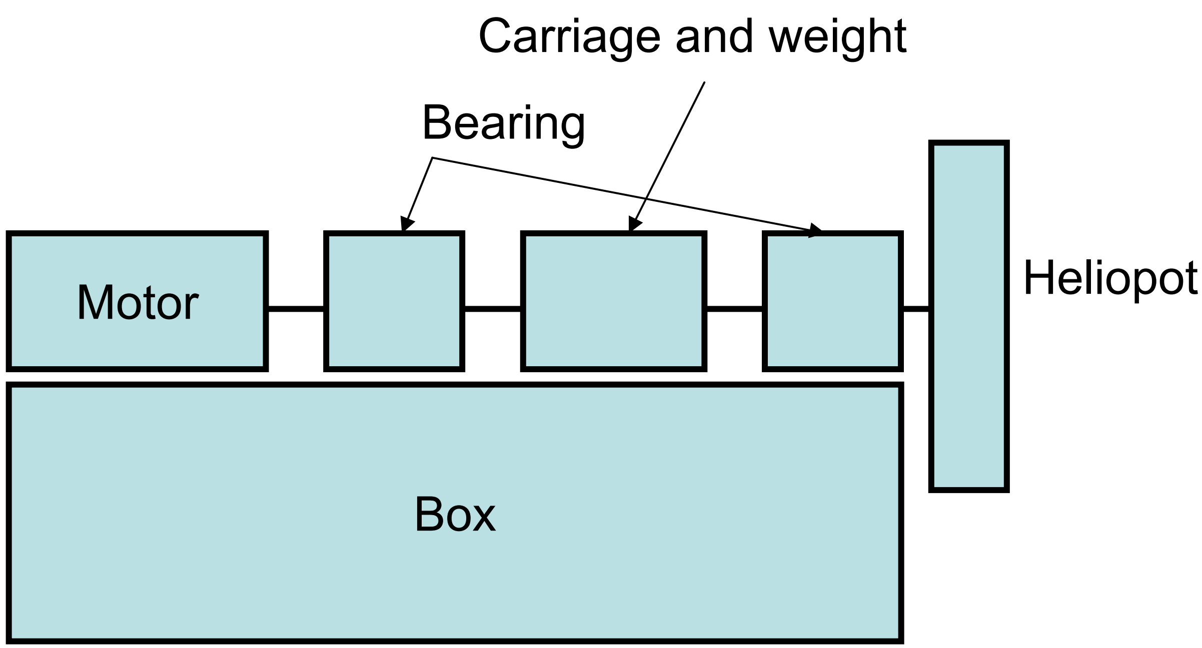
Control Theory and Simulation

- Now you have a control problem. Apply your knowledge of control theory.
- Evaluate/modify plant if required to meet the specifications.
- You may try an optimal design using pole placement. Guidelines for pole placement are given in your textbook.
- Simulate the design and compare the alternatives

A Case Study
Aircraft Pitch Control

This case study offers a chance to step through the design cycle. We will begin by finding the **model** for the plant to be controlled then follow with the **identification** of the parameters of the model. Then we will **design** and **implement** a compensator.

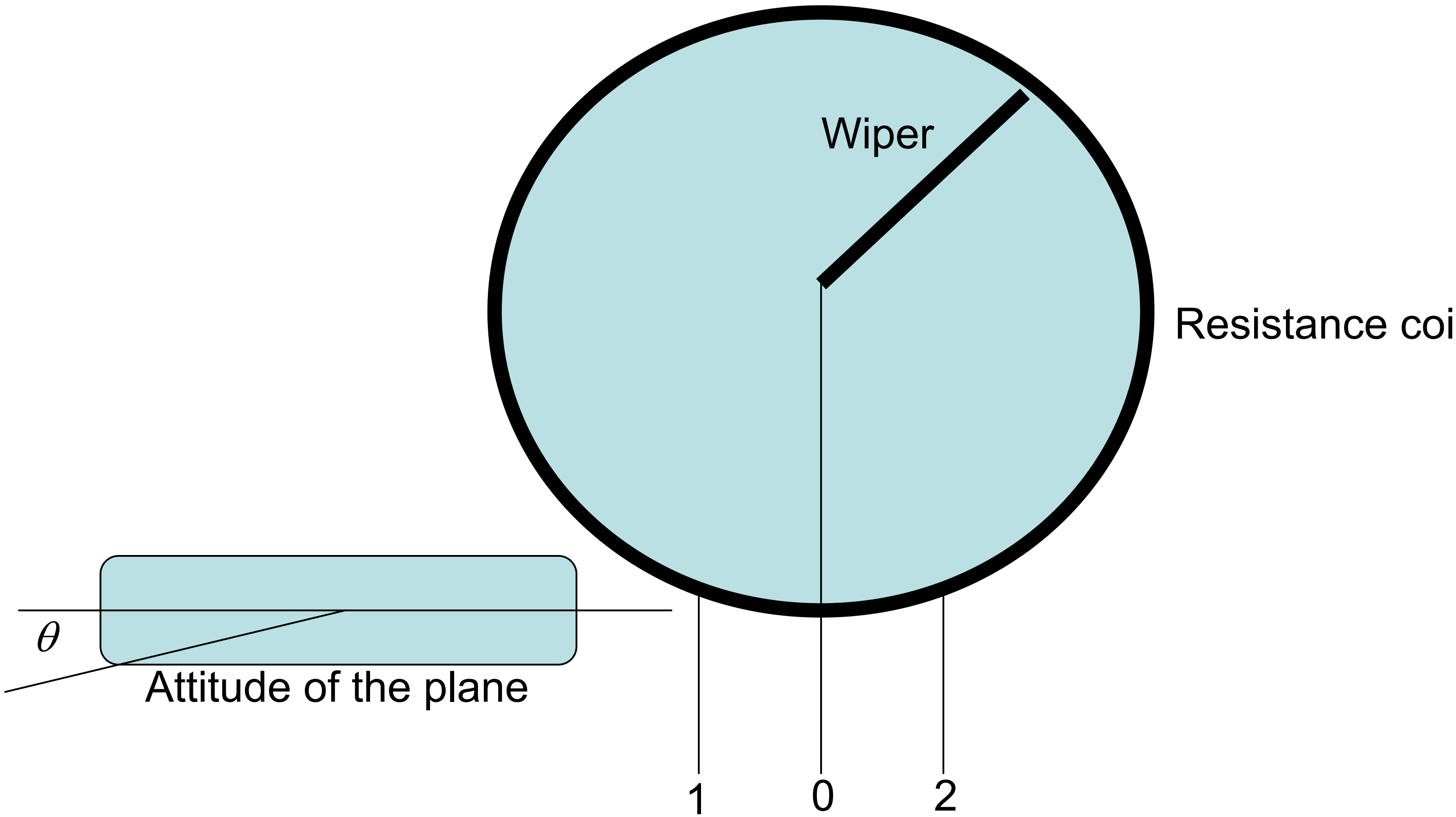
The system to be controlled is shown below. The device consists of a carriage that can rotate. Affixed to the carriage is a weight used to adjust the dynamics of the carriage. Inside the box are two springs that restore the carriage to a horizontal position if the carriage is deflected and then released. The carriage is attached to the shaft of the DC motor at one end, and to a heliopot at the other end. The motor provides the torque to pitch the carriage at a requested angle.



Heliopot

The heliopot senses the angle the carriage makes to the horizontal. It is a very high quality rheostat, with no stops.

By applying voltage between 1 and 2, we can use the wiper voltage to measure the pitch angle of the carriage relative to the horizontal.



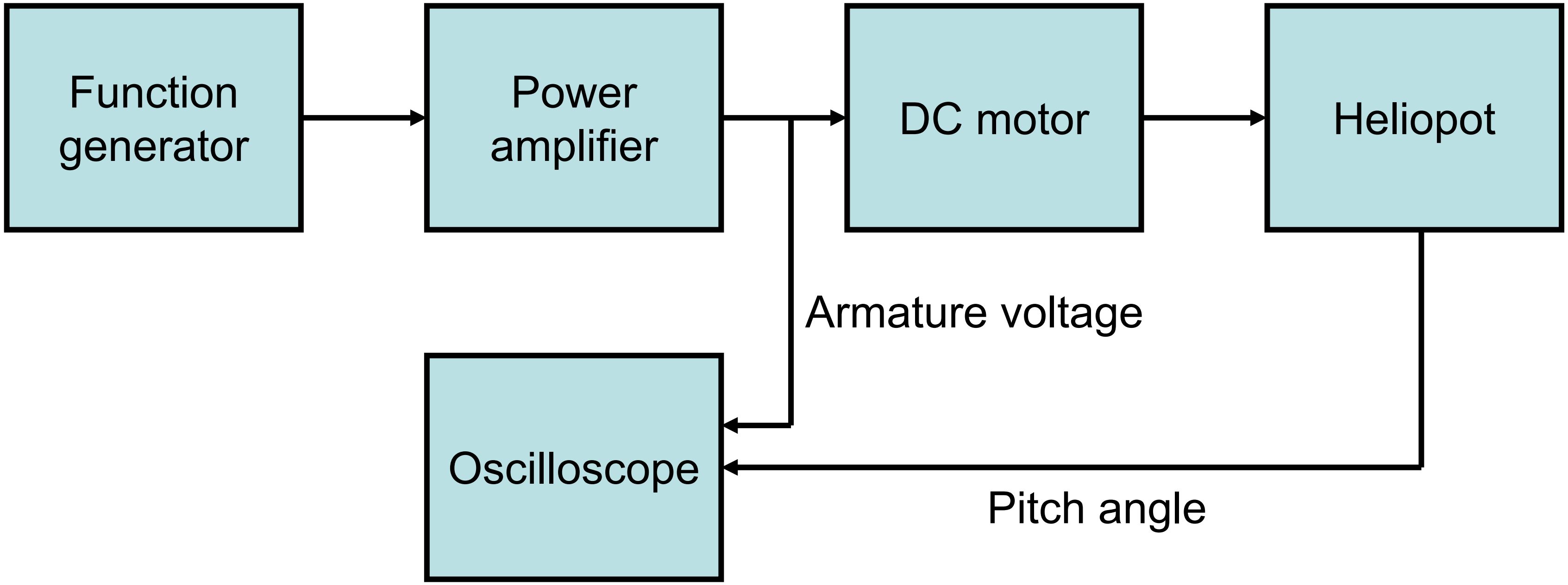
Modeling

- The model to the plant shown in previous figure is the DC motor.
- The carriage changes the overall moment of inertia *J*.
- The springs attached to the carriage apply a restoring torque to the motor shaft.

$$G(s) = \frac{\theta(s)}{V_a(s)} = \frac{K_m}{s\left[(R_a + L_a s)(Js + b) + K_b K_m\right]}$$

$$= \frac{Km}{s(s^2 + 2\xi\omega_n s + \omega_n^2)}$$

Parameter Identification



Data Collection

- Collect magnitude and phase information over a range of frequencies and determine the transfer function.
- Find the location of the dominant complex poles as precisely as possible.
- Find the low-frequency gain of the transfer function.
- We already have the open loop transfer function
- We find the **damping ratio** and **natural frequency** in order to determine the location of the dominant plant poles.

Control Design

- Design a controller for a stable platform.
- Set up the specifications: time to rise; PO; etc.
- Follow the design procedure either by following root locus or Bode plot in order to design the compensator.
- Based on the design specifications select the right compensator: lead; lag or lead/lag.
- In case the controller is digital then transform it to the *z* domain.

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