ME 41100: System Dynamics and Control
Lecture 1: What Is Control and Why Do We Need Feedback?

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Learning Objectives. By the end of this lecture, you should be able to:

- explain what a control problem is and why mechanical engineers use feedback;
- identify reference, input, output, disturbance, sensor, actuator, and controller in a feedback loop;
- distinguish open-loop control, feedforward action, and closed-loop feedback;
- describe the basic control objectives: stabilization, regulation, tracking, and disturbance rejection;
- demonstrate, using a simple mechanical example, how feedback reshapes system dynamics.

1 Course Perspective: What Are We Trying to Learn?

ME 41100 is not a collection of unrelated formulas. The course is organized around one engineering question:

How should we choose the input to a dynamic system so that the system behaves the way we want?

A useful high-level workflow is

$$\text{Physical system} \longrightarrow \text{Model} \longrightarrow \text{Analyze} \longrightarrow \text{Design} \longrightarrow \text{Verify.}$$

Throughout the semester, the mathematics will become more sophisticated, but its purpose will remain the same: to understand the physics and dynamics well enough to predict behavior and shape it deliberately.

What This Course Will Emphasize

- **Modeling:** turn physical laws into differential equations and useful system models.
- **Analysis:** understand transient response, stability, poles and zeros, and frequency response.
- **Design:** choose feedback laws and compensators to achieve performance requirements.
- **Verification:** use analysis, simulation, and experiments to check whether the design actually works.

Question for Discussion

Before designing a controller, what should we know about the system: what can be measured, what inputs can be applied, and how the system responds?

2 What Is a Dynamic System? What Is a Control Problem?

A **dynamic system** evolves over time, and its current behavior depends on its past. In control, we often describe such a system from an input–output viewpoint. We denote the control input by $u(t)$ and the output of interest by $y(t)$.

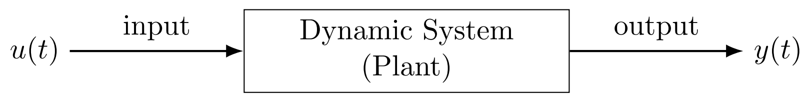

Figure 1: Control-oriented input–output view of a dynamic system.

The control input is a quantity we can manipulate; the output is a quantity we care about. A control problem arises when the system's natural behavior does not meet a desired objective.

2.1 Three Motivating Examples

Cruise Control. The desired speed is the reference, the throttle or brake command is the control input, the powertrain and braking systems provide actuation, vehicle speed is the measured output, and hills or wind act as disturbances. Maintaining a constant speed is a regulation problem; following a changing speed command is a tracking problem.

Room-Temperature Regulation. The desired indoor temperature is the reference, the heating or cooling command is the control input, the HVAC equipment provides actuation, indoor temperature is the measured output, and changes in outdoor temperature and heat transfer through an open door act as disturbances. The objective is to maintain the desired temperature despite these disturbances.

Drone or Inverted Pendulum. Some mechanical systems require continuous corrective action to maintain a desired configuration. A drone must continually adjust its rotor thrusts to maintain its attitude, while an inverted pendulum must continually move its support to remain upright. In both cases, feedback is essential for stabilization rather than merely improving accuracy.

These examples illustrate four recurring control objectives:

- **Stabilization:** prevent divergent or unstable behavior;
- **Regulation:** keep an output near a desired operating point;
- **Tracking:** make an output follow a changing command;
- **Disturbance rejection:** reduce the effect of external disturbances.

In practice, controller design must also balance response speed, overshoot, steady-state error, actuator effort, noise sensitivity, and robustness to model uncertainty.

3 Open-Loop, Feedforward, and Feedback Control

The key structural question is what information is used to determine the control input. Open-loop control uses a predetermined command, feedforward control anticipates the required action using command or disturbance information, and feedback control uses the measured output to correct the control action.

3.1 Open-Loop Control

In open-loop control, the control input is generated without using a measurement of the output. Because the action is not corrected based on the system's actual response, performance depends strongly on calibration and is sensitive to disturbances and changes in the plant.

3.2 Feedforward Control

Feedforward control uses the reference and/or a measured disturbance to anticipate the required control action before an error appears at the output. It can respond quickly, but its effectiveness depends on the accuracy of the plant and disturbance models. Feedforward remains open with respect to the output and can be used alone or combined with feedback.

3.3 Closed-Loop Feedback

In feedback control, the actual output is measured and compared with the desired output. If the reference is $r(t)$ and the measured output is $y(t)$, the error is

$$e(t) = r(t) - y(t). \tag{1}$$

The controller uses this error, together with any other available information, to compute a corrective action.

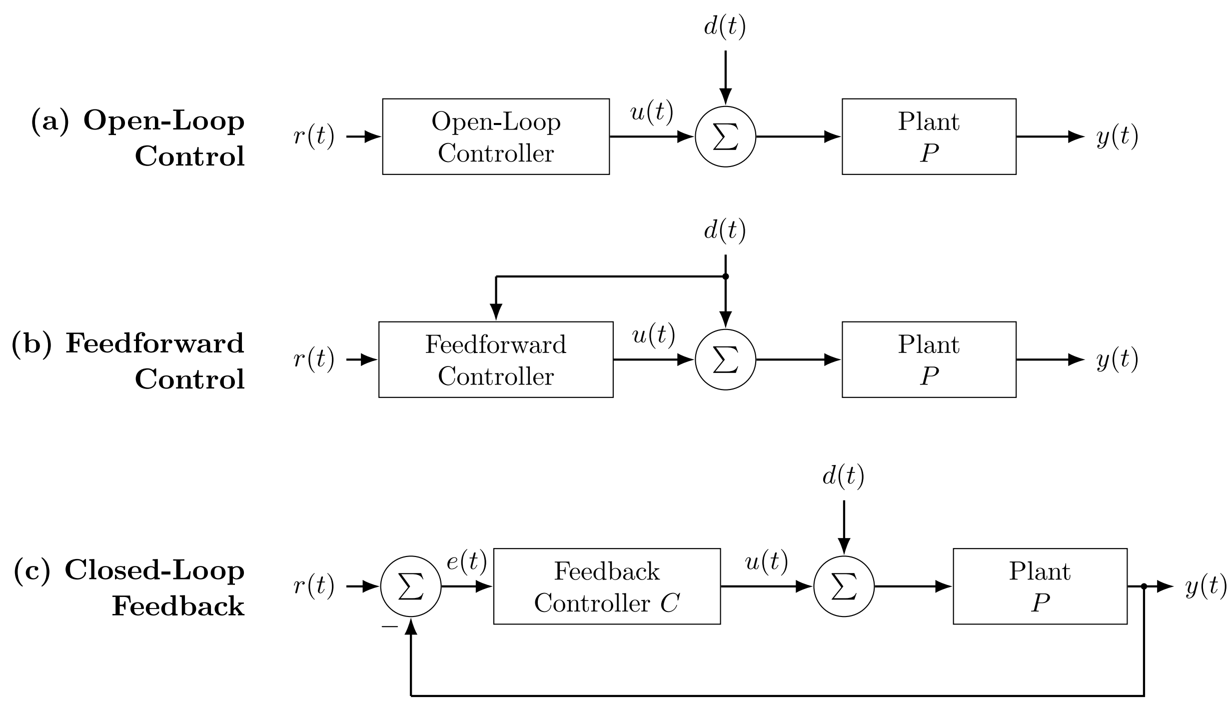

Figure 2: Information paths in open-loop, feedforward, and feedback control. Feedforward anticipates the required action using command and/or measured-disturbance information; feedback corrects the action using the measured output.

3.4 Why Use Feedback?

Feedback is valuable because real engineering systems are never modeled perfectly and are subject to disturbances, parameter variations, unmodeled dynamics, and changing operating conditions. At the same time, feedback design must account for sensor noise and actuator limitations.

A basic qualitative comparison is shown in Table 1.

Table 1: Qualitative comparison of feedback and feedforward.

Comparison	Feedback	Feedforward
Loop structure	Closed loop	Open with respect to output
Basis for action	Reference and measured output (error)	Reference and/or measured disturbance
Disturbance response	Corrects after the effect appears at the output	Acts in advance if the disturbance is measured or predicted
Model dependence	Typically less sensitive to moderate model error	Strongly dependent on model accuracy
Main limitation	Poor design can amplify noise or destabilize the loop	Cannot correct unmeasured effects; model errors produce incorrect actions

Feedback can remain effective with an imperfect model. By measuring the actual output, it can correct deviations caused by disturbances and model uncertainty. This ability provides robustness. However, poorly designed feedback can amplify sensor noise, demand excessive actuator effort, or destabilize the closed loop.

4 What Is Inside a Physical Feedback Loop?

A real control system contains more than a mathematical controller. It usually includes a *sensor*, a *computing unit*, an *actuator*, and the *physical plant*. Disturbances and noise can enter at different locations.

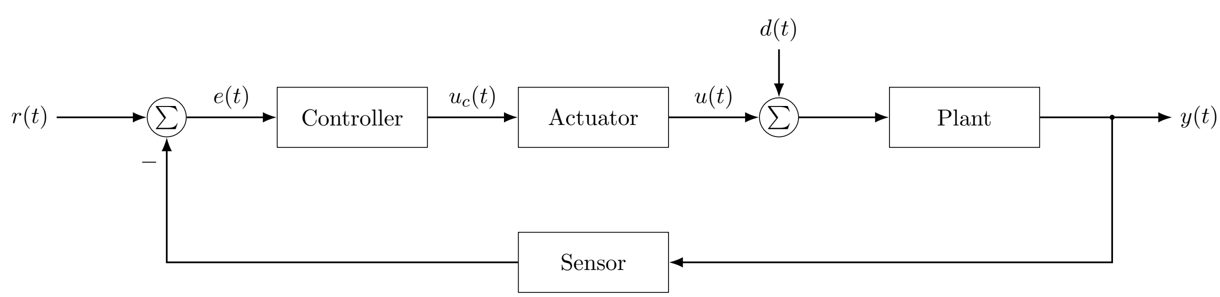

Figure 3: Generic physical feedback loop.

A useful conceptual summary is:

Sense $\longrightarrow$ Compare $\longrightarrow$ Compute $\longrightarrow$ Actuate $\longrightarrow$ Plant Responds $\longrightarrow$ Sense Again

5 The Roadmap of ME 41100

ME 41100 follows an iterative engineering workflow. We begin with a physical system, build a dynamic model, choose a useful mathematical representation, analyze the dynamics, design a controller, and verify performance. The results then inform the next modeling and design cycle.

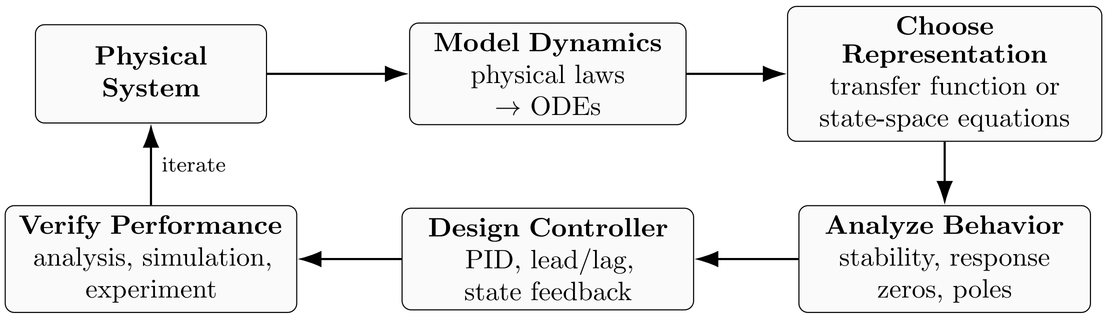

Figure 4: The iterative workflow that organizes ME 41100.

The course develops the tools needed to carry out this workflow:

- **Modeling:** derive differential-equation models from physical laws.
- **System representation:** express dynamic models using transfer functions and state-space equations.
- **Dynamic analysis:** use transient response, poles, and zeros to understand system behavior and stability.
- **Classical control design:** use root locus, PID control, and lead/lag compensation to shape closed-loop dynamics.
- **Frequency-domain analysis:** use Bode and Nyquist methods to study bandwidth, stability margins, and robustness.
- **State-space methods:** analyze and design multivariable systems using internal-state models.
- **Verification:** evaluate the final design through analysis, simulation, and experiment.

The recurring question throughout ME 41100 is:
How does the closed-loop system behave, and how can we shape and verify that behavior?

6 A Short Mechanical Example: Feedback Reshapes Dynamics

Consider the mass–spring–damper system in Figure 5. Let $x(t)$ be the displacement of the mass and $u(t)$ the applied control force.

Newton's second law gives

$$m\ddot{x}(t) + b\dot{x}(t) + kx(t) = u(t). \tag{2}$$

Suppose the control objective is for $x(t)$ to track a constant reference r. A simple proportional feedback law attempts to achieve this objective:

$$u(t) = K\big(r - x(t)\big), \qquad K > 0. \tag{3}$$

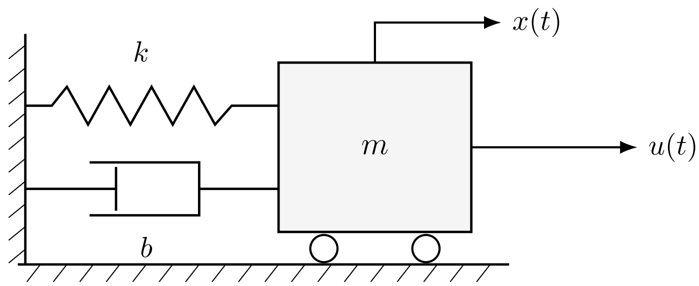

Figure 5: Mass–spring–damper system with applied control force $u(t)$.

Substituting (3) into (2) gives

$$m\ddot{x}(t) + b\dot{x}(t) + (k + K)x(t) = Kr. \tag{4}$$

Because the control input now depends on $x(t)$, the feedback law changes the differential equation governing the system. Equation (4) gives the effective stiffness and natural frequency and, for a constant reference, the equilibrium position and steady-state error:

$$k_{\text{eff}} = k + K, \qquad \omega_n = \sqrt{\frac{k+K}{m}}, \qquad x_{\text{ss}} = \frac{K}{k+K}\,r, \qquad e_{\text{ss}} = \frac{k}{k+K}\,r.$$

Increasing K therefore makes the system stiffer and raises its natural frequency, while reducing—but not eliminating—the steady-state error for finite K. The physical damping coefficient remains b, although the damping ratio $\zeta = b/[2\sqrt{m(k+K)}]$ changes. In practice, large K can also demand greater transient control force and make actuator limits, sensor noise, and neglected dynamics more important.

Feedback changes both the equilibrium response and the dynamics.

Question for Discussion

Which effects of increasing K on equilibrium, response speed, and oscillation can be inferred directly from Equation (4)? Which require a transient-response analysis?

7 Feedback in Modern Autonomous Systems

Modern autonomous systems place perception, state estimation, planning, and decision-making around a physical feedback loop. Planning converts a mission objective into a reference $r(t)$. Sensors provide measurements, an estimator reconstructs the system and environment state, and the feedback controller computes commands that make the physical system follow the reference.

The outer autonomy layers determine *what* the system should do; the feedback loop determines *how* to execute that objective despite disturbances, uncertainty, and imperfect models. This distinction applies to cruise-controlled vehicles, robot arms, inverted pendulums, autonomous drones, and many other engineered systems.

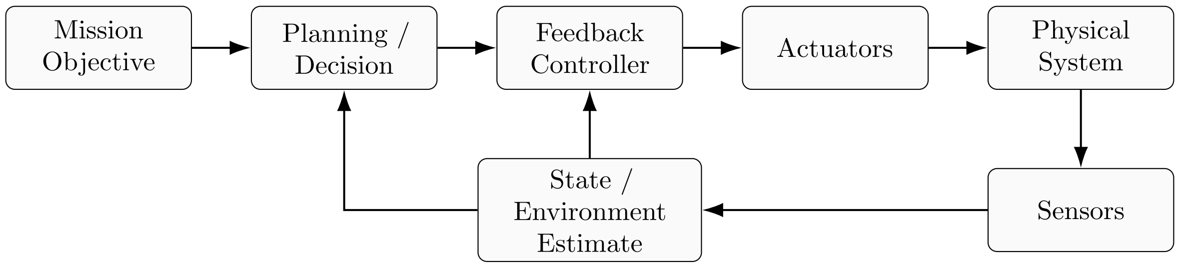

Figure 6: A simplified autonomy architecture. Planning supplies a reference, while estimation and feedback close the physical loop.

8 Main Takeaways

1. Control shapes the behavior of dynamic systems through deliberately designed inputs and control laws.
2. Feedback uses measured outputs to adjust the control action. It can improve disturbance rejection and robustness, but poor design can amplify noise or destabilize the system.
3. A practical feedback system includes a reference, sensing, a controller or computing unit, actuation, and the physical plant.
4. Models, transfer functions, state-space equations, poles and zeros, root locus, frequency response, and controller-design methods provide complementary ways to analyze and shape system behavior.
5. Control design is iterative:
   Physical System → **Model** → **Represent** → **Analyze** → **Design** → **Verify** → **Iterate**.

Homework

Reading: Read Chapter 1 of *Feedback Systems: An Introduction for Scientists and Engineers*, then answer the questions below.

1. Identify one feedback system you used today. What are its reference, measured output, sensor, actuator, plant, and principal disturbance?
2. Under what conditions can feedback reduce the effect of a disturbance that was not explicitly included in the controller design?
3. Why does feeding the measured output back not automatically guarantee improved performance or stability?
4. In the mass–spring–damper example, what happens if $b = 0$? How does the feedback gain K affect the natural frequency, and can proportional feedback alone make the motion decay?
5. When might a simple approximate model be more useful for control design than a highly detailed model?