

Chapter 1: Introduction to Control Systems

Signals, feedback, design language, and a recurring DC servo

Gang Chen

South China University of Technology

Course Syllabus and Assessment

Textbook: Dorf, R. C. & Bishop, R. H., *Modern Control Systems*, 14th Ed.

30%

Midterm Examination

Understanding of
fundamental concepts

40%

Final Examination

Comprehensive mastery
of the course

30%

Homework and Class Performance

Assignments, participation,
and classroom engagement

Consistent participation and timely completion of homework are essential for success in this course.

Why control? Make behavior repeatable

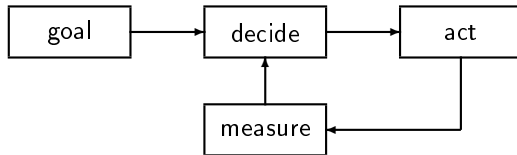
Without deliberate control

A physical process responds to commands, disturbances, uncertainty, and noise on its own terms.

- A motor slows under load.
- A room drifts as outdoor temperature changes.
- A read head misses a rapidly moving track.

With a control system

Sensors reveal what happened; a controller chooses an action that moves behavior toward a stated goal.



Learning outcomes and chapter route

Learning outcomes

- Distinguish open-loop action from closed-loop negative feedback.
- Label r , e , u , y , d , and n and trace cause to effect.
- Translate a need into variables, specifications, a configuration, and evidence.
- Use MATLAB and Simulink assertions to support introductory claims.

Need $\rightarrow$ signals $\rightarrow$ topology $\rightarrow$ model $\rightarrow$ response $\rightarrow$ specification decision

Recurring problem: a DC servo under load

Course design story

Rotate a motor shaft to commanded angle r ; measure angle, drive the armature with voltage u , and reject an unknown load torque d despite sensor noise n .

- controlled output: y , shaft angle (rad)
- manipulated input: u , armature voltage (V)
- measured output: $y_m = y + n$

Design check

Initial targets, refined later:

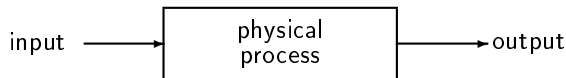
$$\begin{aligned} t_s &\leq 1 \text{ s}, & M_p &\leq 10\%, \\ |e_{ss}| &\leq 0.02 \text{ rad}, & |u| &\leq 12 \text{ V}. \end{aligned}$$

1.1 Introduction: system, input, output, purpose

Control system

An interconnection of components arranged to produce a desired response.

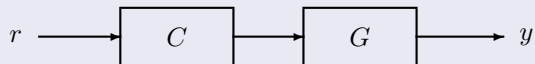
- **System**: boundary chosen for analysis.
- **Input**: cause entering that boundary.
- **Output**: effect we observe or regulate.
- **Purpose**: the behavior we want.



A model records the causal input–output relationship at a useful level of detail.

Open loop and closed loop answer different questions

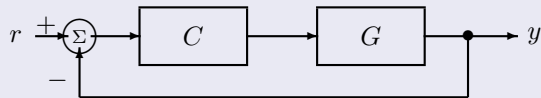
Open loop



“What output follows from a preselected action?”

- simple and inexpensive
- cannot correct unseen output error

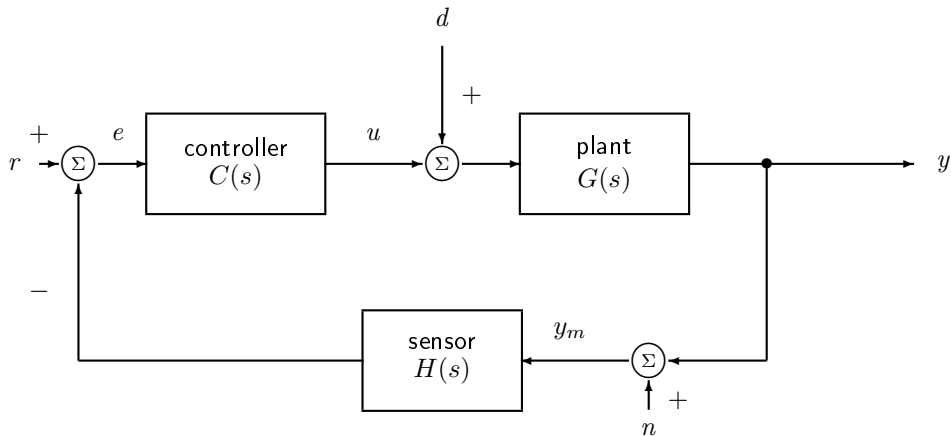
Closed loop



“How should action change after measuring the result?”

- can reduce effects of disturbances
- requires stability and noise analysis

Signal convention: one diagram for the course



r – reference

e – error

u – control effort

y – output

d – plant-input disturbance

n – measurement noise

Interaction: Label r, e, u, y, d, n

A motorized camera must track a desired angle while wind torque pushes the mount and encoder electronics add noise.

- 1 Assign each physical quantity to r , e , u , y , d , or n .
- 2 Which signals are chosen by the designer, measured, or imposed by the environment?
- 3 Trace the causal direction from command to output and from output back to error.

Pair protocol – 90 seconds

Agree on one signal map, then choose one speaker to justify every arrow and injection point before the class reveal.

Negative-feedback algebra exposes the causal paths

With unity sensing, $e = r - y$, $u = C(s)e$, and $y = G(s)[u + d]$.

$$\begin{aligned}y &= GC(r - y) + Gd, \\(1 + GC)y &= GCr + Gd, \\y &= \underbrace{\frac{GC}{1 + GC}}_{T(s)} r + \underbrace{\frac{G}{1 + GC}}_{\text{plant-input disturbance path}} d.\end{aligned}$$

One denominator, two design questions

The loop $L = GC$ shapes both command tracking and disturbance rejection; the numerators show why the two paths are not identical.

Disturbance and noise enter at different locations

Plant-input disturbance d

Load torque, wind force, or heat leakage changes the physical process input.

$$\frac{Y}{D} = \frac{G}{1 + GCH}.$$

Larger stable loop gain tends to suppress its effect.

Measurement noise n

Encoder quantization or electrical interference corrupts what the controller sees.

$$\frac{Y}{N} = -\frac{GC}{1 + GCH}.$$

High loop gain can transmit noise to output and control effort.

Feedback is a trade-off mechanism, not a universal improvement switch.

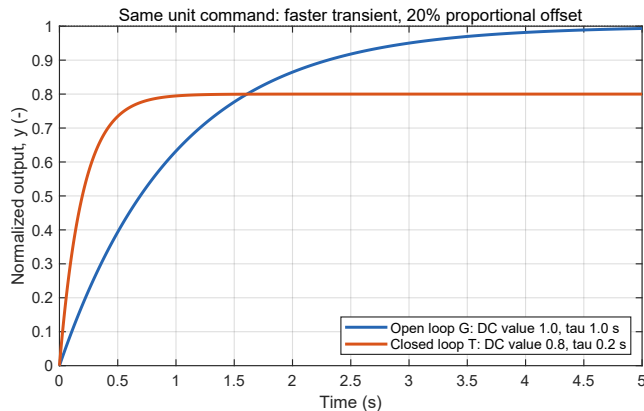
Interaction: Predict open/closed-loop disturbance behavior

A unit step disturbance is added at the input of $G(s) = 1/(s + 1)$ at zero reference. Compare open loop with proportional negative feedback $C = 4$.

- 1 Before calculating, sketch the two output deviations.
- 2 Which response should be faster? Which should have the smaller final deviation?
- 3 Use $Y/D = G/(1 + GC)$ to predict the closed-loop DC value.

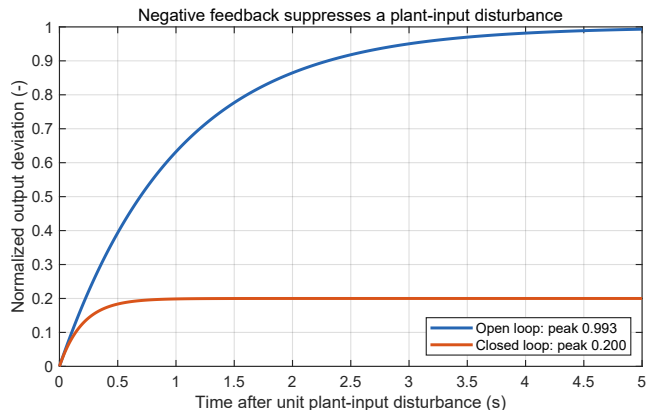
Commit before the reveal: write both DC values and one sentence explaining the direction of change.

MATLAB evidence: faster transient, nonzero offset



Same unit command, $G = 1/(s + 1)$ and $T = 4G/(1 + 4G)$. The time constant falls from 1 s to 0.2 s, but $G(0) = 1$ and $T(0) = 0.8$: proportional feedback has 20% unit-step steady-state error. Unity tracking needs integral action or a correctly designed reference prefilter.

MATLAB evidence: plant-input disturbance rejection



The disturbance paths are $G = 1/(s + 1)$ and $G/(1 + 4G) = 1/(s + 5)$. Their DC gains are 1 and 0.2, so the *asymptotic* deviation is one fifth; at the finite 5 s horizon, the plotted samples are 0.993 and 0.200.

Interaction: Interpret the two step plots

In groups of three, make one claim from each plot and attach the correct evidence.

- 1 What can the tracking plot prove at 1 s? What can it *not* prove about steady state?
- 2 What exact transfer functions explain the disturbance plot?
- 3 Identify one benefit and one cost of using proportional gain 4.

Design check

A curve is evidence only when its input, model, axes, horizon, and comparison quantity are stated.

Reversing the sign changes the denominator

For negative feedback with $G = 1/(s + 1)$ and $C = 4$,

$$T_-(s) = \frac{4G}{1 + 4G} = \frac{4}{s + 5}, \quad \text{pole } s = -5.$$

If the measured output is *added* instead of subtracted,

$$T_+(s) = \frac{4G}{1 - 4G} = \frac{4}{s - 3}, \quad \text{pole } s = +3.$$

Physical meaning

A positive output produces more action in the same direction; the deviation reinforces itself instead of being corrected.

Interaction: Diagnose a reversed feedback sign

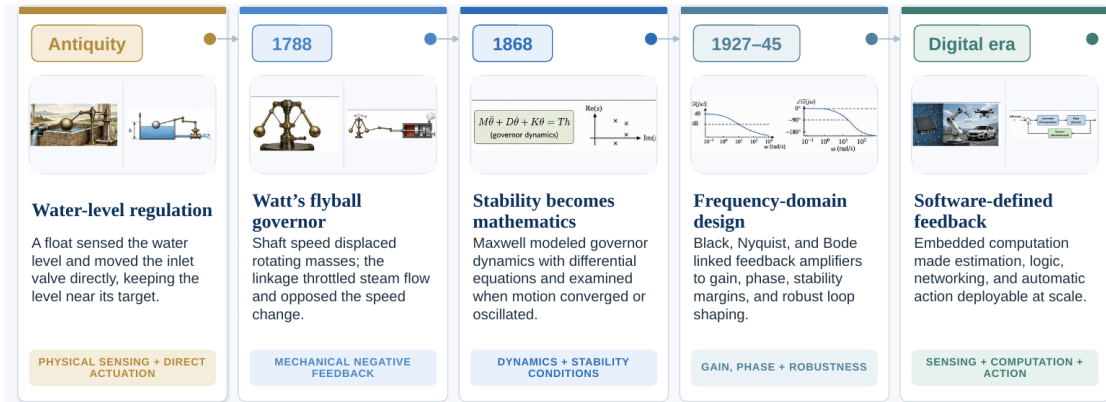
A servo moves farther from its command immediately after a sensor wire is replaced. The controller code and plant are unchanged.

- 1 Mark the sign at the comparison junction that would create this symptom.
- 2 Give a safe, low-amplitude commissioning test that distinguishes sign error from low gain.
- 3 State the expected response if negative feedback is restored.

Safety first

De-energize before rewiring; test with actuator limits and an emergency stop. A sign error is a structural fault, not a tuning problem.

1.2 Brief History: feedback predates electronics



The hardware changes; the compare-act-measure loop persists.

History is a sequence of design constraints

Mechanical

Local sensing and actuation; geometry embodies the controller.

Analog electronic

Amplifiers enable high bandwidth; stability theory becomes essential.

Digital/networked

Algorithms add flexibility; sampling, delay, software, and cybersecurity enter the loop.

Design check

Every implementation still needs a physical variable, sensor, actuator, causal model, and verifiable specification.

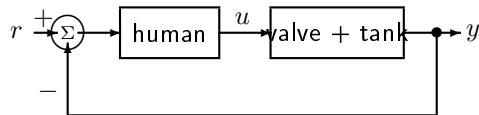
1.3 Examples: recognize the same loop in many domains

Application	Output y	Actuator/control u	Disturbance d
Vehicle steering	heading	steering angle	crosswind
Fluid tank	liquid level	outlet valve	inlet-flow change
Power grid	frequency/voltage	generator commands	load variation
Insulin delivery	glucose level	infusion rate	meals/exercise
Robot joint	angle/speed	motor voltage	contact torque

Domain vocabulary changes; signal roles and design questions transfer.

Worked example: human-in-the-loop tank control

- 1 Goal: hold fluid level at a marked reference.
- 2 Sensor: operator's vision estimates actual level.
- 3 Comparator/controller: operator judges error.
- 4 Actuator: hand changes outlet-valve opening.
- 5 Disturbance: inlet flow changes.



Human perception and reaction delay
constrain achievable performance.

Worked example: map the DC servo signals

Signal	Physical quantity	Instrument or cause
r	commanded shaft angle (rad)	motion planner
e	command minus measured angle (rad)	digital subtraction
u	armature voltage (V)	power amplifier
y	actual shaft angle (rad)	motor/load mechanics
d	opposing load torque (N m)	environment
n	encoder measurement error (rad)	quantization/electronics

Causal test

Changing u must be able to change y ; changing y must change the measured feedback and therefore e .

1.4 Engineering Design: create, analyze, iterate

Synthesis

Propose a configuration: components, signal paths, materials, algorithms, and interfaces.

Analysis

Predict whether a proposed configuration meets measurable requirements.

Why iteration is unavoidable

Complexity, competing objectives, model-to-reality gaps, schedule, cost, and risk prevent a one-pass design.

need → propose → test → revise

Specifications turn adjectives into decisions

Vague wish	Measurable specification	Evidence
“fast”	$t_s \leq 1\text{ s}$	step response and settling band
“accurate”	$ e_{ss} \leq 0.02\text{ rad}$	final-value calculation/simulation
“well damped”	$M_p \leq 10\%$	peak relative to final value
“reject loads”	$\max \Delta y \leq 0.05\text{ rad}$	stated disturbance test
“practical”	$ u(t) \leq 12\text{ V}$	actuator trace and saturation limit

A useful specification states a variable, metric, numerical bound, operating condition, and unit.

1.5 Control System Design: seven steps in three groups

1. Goals and metrics

- ① establish goals
- ② identify controlled variables
- ③ write specifications

2. Definition and model

- ④ establish configuration
- ⑤ model process, actuator, sensor

3. Design and evidence

- ⑥ select controller and parameters
- ⑦ optimize, simulate, analyze

If evidence misses a specification, iterate the configuration or revisit the specification.

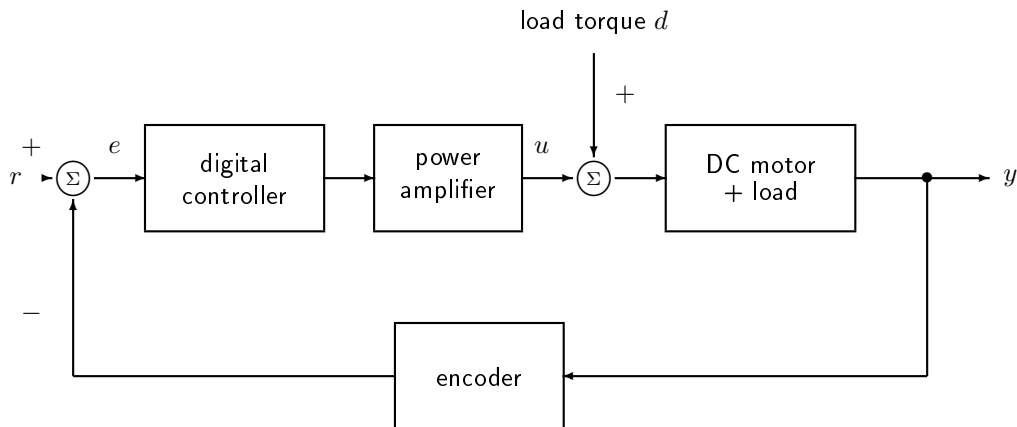
Worked design: servo goals, variables, and specifications

- 1 **Goal:** point a small load to a commanded angle despite load torque.
- 2 **Controlled variable:** shaft angle y in rad; error $e = r - y_m$.
- 3 **Initial command test:** 0.5 rad step, no disturbance.
- 4 **Initial disturbance test:** 0.02 N m load-torque step at steady command.
- 5 **Metrics:** t_s , M_p , e_{ss} , peak output deviation, peak voltage.

Design check

Targets are not yet proof. Chapters 2–9 will build models and analysis methods that turn these statements into defensible design decisions.

Worked design: establish the servo configuration



Candidate component parameters are fixed in the shared course interface; the controller and its gains are the design choices.

Worked calculation: the first-order teaching plant

Let $G(s) = 1/(s + 1)$ and $C(s) = 4$ with unity negative feedback.

Command path

$$\frac{Y}{R} = \frac{4G}{1 + 4G} = \frac{4}{s + 5}.$$

Pole: -5 ; time constant: 0.2 s ; DC value: 0.8 .

Disturbance path

$$\frac{Y}{D} = \frac{G}{1 + 4G} = \frac{1}{s + 5}.$$

Pole: -5 ; time constant: 0.2 s ; DC value: 0.2 .

The same pole sets speed; different numerators set command and disturbance gains.

Worked calculation: convert response into specifications

For a first-order response, the 2% settling-time approximation is $t_s \approx 4\tau$.

$$t_{s,\text{open}} \approx 4(1) = 4\text{ s},$$

$$e_{ss,\text{closed}} = 1 - T(0) = 0.2,$$

$$t_{s,\text{closed}} \approx 4(0.2) = 0.8\text{ s},$$

$$\Delta y_{ss}/d_0 = 0.2.$$

Design check

The closed loop meets a 1 s settling target and improves disturbance rejection, but it fails any unit-step error target tighter than 0.2. The next design iteration needs a different controller structure, not a misleading plot scale.

MATLAB evidence is executable, not decorative

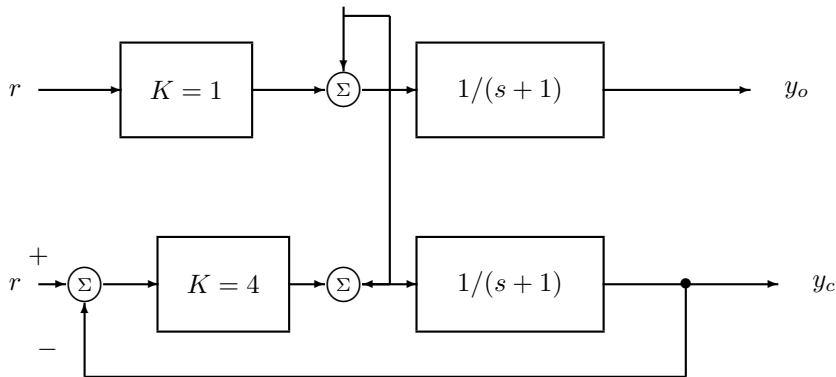
```
G = tf(1,[1 1]);  
T = feedback(4*G,1);  
assert(abs(dcgain(G)-1) < 1e-12);  
assert(abs(dcgain(T)-0.8) < 1e-12);  
assert((-1/real(pole(T))) < (-1/real(pole(G))));  
exportgraphics(fig,file,'ContentType','vector');
```

Separate analytic checks

The script also asserts $G(0) = 1$, $T(0) = 0.8$, and a smaller closed-loop disturbance peak. This prevents a transient sample from being misreported as a steady-state result.

Simulink model: two branches, one disturbance

d : step at 4s



Programmatic blocks include reference, sums, proportional controller, first-order plants, disturbance, sensor, scopes, and To Workspace evidence sinks.

Paired Simulink assertions isolate the disturbance

The builder saves `ch01_open_closed_loop.slx`, then runs the same reference case twice with disturbance amplitude 0 and 1:

- 1 a fixed 0.01 s grid makes paired log times identical;
- 2 subtract on/off outputs and errors sample by sample;
- 3 assert finite differences and $\Delta e = -\Delta y$;
- 4 at 8 s: $\max |\Delta y_o| = 0.981715$ and $\max |\Delta y_c| = 0.200000$.

Why this metric?

The subtraction cancels the common command response. The sampled ratio is 0.2037; the asymptotic (DC) attenuation is exactly 0.2.

1.6 Mechatronic Systems: design the interfaces together

- mechanics set inertia, friction, compliance, and range;
- electronics condition sensing and deliver actuator power;
- computation implements logic, estimation, and control;
- communication introduces sampling, delay, and failure modes.

Mechatronic performance belongs to the integrated loop, not to one component.

Servo consequence

A controller cannot recover angle information the encoder never resolves, create torque beyond the amplifier limit, or remove a mechanical resonance ignored by the model.

1.7 Green Engineering: feedback as an enabling technology

Systems view

Measure environmental and energy variables across the life cycle; regulate operation to reduce waste while protecting performance and safety.

- wind-turbine load and power control
- solar conversion and storage management
- power-quality monitoring

Design check

“Greener” needs a metric: energy per task, peak demand, material use, emissions, lifetime, or environmental risk – plus a declared boundary and operating condition.

1.8 Future Evolution: flexibility and autonomy

Fixed automation pathway

Highly repeatable behavior in a structured environment; richer sensing and programming increase flexibility.

Supervised-control pathway

Adaptable human-directed systems; better perception, interfaces, and decision support increase autonomy.

Core lecture boundary

Model predictive control, Kalman filtering, robust control, and MIMO methods are **Reference** topics here. Later chapters first establish the models, stability, and performance tools needed to study them responsibly.

1.9 Design Examples: compare decisions, not domains

System	Goal/variable	Configuration	Critical evidence
Smart grid	reliable voltage/frequency	distributed sensing and actuation	disturbance scenarios, constraints
Rotating disk	regulate speed	motor, sensor, feedback controller	command and load responses
Insulin delivery	regulate glucose	continuous sensor and pump	patient safety and uncertainty

All three require goals, variables, specifications, models, a candidate loop, and evidence; their risks and acceptable experiments differ.

A checked design-evidence workflow

- ➊ Derive the expected transfer path and limiting values.
- ➋ Encode the model and scenario with units and parameters.
- ➌ Assert the numerical comparison that supports the claim.
- ➍ Export vector evidence with labeled axes and legend.
- ➎ Cross-check plot, assertion, and specification language.

Chapter 1 evidence set

Two MATLAB vector plots and one programmatically built Simulink model support the feedback vocabulary and the stated first-order comparisons.

1.10 Disk Drive Sequential Example: freeze the first decisions

- ❶ **Goal:** position the reader head over the selected track.
- ❷ **Controlled variable:** head position.
- ❸ **Initial specifications:** accuracy about $1\text{ }\mu\text{m}$; track-to-track move within 50 ms, if feasible.
- ❹ **Configuration:** control device, actuator motor/read arm, position sensor, negative feedback.

Sequential promise

Chapter 2 supplies component models; later chapters analyze feedback characteristics, performance, stability, and controller design for the same problem.

Chapter synthesis: one loop, six signals, seven design steps

- Negative feedback forms $e = r - y_m$; the sign determines whether deviations are corrected or reinforced.
- d acts on the physical plant input; n corrupts the measurement. Location determines the transfer path.
- A specification is a measurable bound under a declared test condition.
- MATLAB/Simulink evidence is credible when equations, parameters, assertions, and plots agree.
- The DC servo and disk-drive read head carry this vocabulary into Chapters 2–9.

Exit ticket and bridge to Chapter 2

- 1 Write e for unity negative feedback and state the causal meaning of the minus sign.
- 2 For $G = 1/(s + 1)$ and $C = 4$, give Y/R and Y/D .
- 3 Rewrite “the servo should be fast” as one numerical specification with units and a test input.
- 4 Name the missing ingredient needed before tuning a real DC servo: a defensible model of motor, load, actuator, and sensor.

Homework

E1.2, E1.7, E1.12, P1.5, P1.6, P1.9

homework send to **homeworkscut2026@126.com**, **due on Sept.10,2026.**