ECE 1675/2570: Robotic Control (Spring 2022)

Module I: Robotics and Controls Primer

Lecture 1: Course Organization and Introduction to Robotic Control

January 12, 2022

Zhi-Hong Mao
Professor of ECE and Bioengineering
University of Pittsburgh, Pittsburgh, PA

1

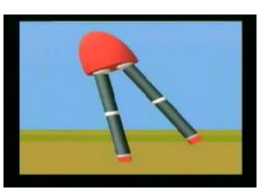
Outline

- Course description
- Course organization
- Introduction to robotics
- Introduction to control theory
- An example of control design: cruise control

2

Course description

- This course focuses on the application of control theory in robotics
  - Why did I develop this course?
    - My related research interests and experiences



MIT M2 robot simulation (John Hu)

Troody dinosaur (Peter Dilworth)

3

Course description

- This course focuses on the application of control theory in robotics
  – Why did I develop this course?
    - My related research interests and experiences

Dimensionality reduction in neural control of the hand (Ramana Vinjamuri at Pitt)

HEXOES: Hand exoskeleton (Ramana Vinjamuri at UMBC)

4

Borrowing ideas from biological world

Mao's area - modeling basal ganglia

Course description

- This course focuses on the application of control theory in robotics
  – Why did I develop this course?
    - My related research interests and experiences
    - My effort in developing this course
      - My initial (failed) effort
      - Robotics courses from Georgia Tech (Dr. Magnus Egerstedt), MIT (Dr. Russ Tedrake), Stanford (Dr. Oussama Khatib), University of North Carolina at Charlotte (Dr. James Conrad), and Saint Martin's University (Dr. Rico Picone)

5

Course description

- This course focuses on the application of control theory in robotics
  – Why did I develop this course?
    - My related research interests and experiences
    - My effort in developing this course
    - Features of the *"Pitt robotics"* course
      - *Depth:* focusing on control design methods and mathematical foundation of robotics
      - *Breadth:* covering mobile robotics, manipulator robotics, and cognitive robotics

6

Course description

- This course focuses on the application of control theory in robotics
  - Why did I develop this course?
  - What is ***not*** in the lecture part of this course?
    - Circuit design
    - Programming
    - Perception
    - Mechanical engineering
    - AI

7

Course description

- This course focuses on the application of control theory in robotics
- Review of classical and modern control design methods
  - PID control
  - State feedback
  - Optimal control
  - Adaptive control
  - Hybrid control
  - Reinforcement learning

8

Course description

- This course focuses on the application of control theory in robotics
- Review of classical and modern control design methods
- Control of mobile robots

9

Course description

- This course focuses on the application of control theory in robotics
- Review of classical and modern control design methods
- Control of mobile robots
- Control of robot manipulators

10

Course description

- This course focuses on the application of control theory in robotics
- Review of classical and modern control design methods
- Control of mobile robots
- Control of robot manipulators
- Some advanced topics (if time permits)
  - Cognitive robotics
  - Human-robot interaction

11

Course description

- This course focuses on the application of control theory in robotics
- Review of classical and modern control design methods
- Control of mobile robots
- Control of robot manipulators
- Some advanced topics (if time permits)
- The course is organized into four modules
  - Module I: Robotics and controls primer (~4 lectures)
  - Module II: Control of mobile robots (~6 lectures)
  - Module III: Control of robot manipulators (~3 lectures)
  - Module IV: Advanced topics (~1 lecture)

12

Course organization

- Times and places
  - Lectures
    - Wednesday 6 pm-8:30 pm
    - Zoom link: https://pitt.zoom.us/j/6288281300
  - Labs (for ECE 1675 students only)
    - Friday 3 pm-5:30 pm
    - Zoom link: https://pitt.zoom.us/j/7817111574, passcode: 210324

Can audit

13

Course organization

- Times and places
- Instructors
  - Lecture part: Zhi-Hong Mao
    - (Zoom link) https://pitt.zoom.us/j/6288281300
    - (Email) maozh@engr.pitt.edu
    - (Office hours) Monday 3:30 pm-5 pm
  - Lab part (ECE 1675): Boyang Li
    - (Zoom link) https://pitt.zoom.us/j/7817111574, passcode: 210324
    - (Email) bol33@pitt.edu

14

Course organization

- Times and places
- Instructors
- Reading material
  - Lecture notes
    - To be sent to you by emails
    - Also available for download at Canvas
  - Recommended textbooks Required
    - M. Mataric, The Robotics Primer, MIT Press, 2007
    - K. J. Astrom and R. M. Murray, Feedback Systems: An Introduction for Scientists and Engineers, Princeton University Press, 2010

15

Course organization

- Times and places
- Instructors
- Reading material
- Evaluation
  - Undergraduate ECE 1675 (4 credits)
    - Homework: 15%
    - Class participation: 10%
    - Midterm: 25%
    - Final exam: 35%
    - Lab: 15%

Course organization

- Times and places
- Instructors
- Reading material
- Evaluation
  - Undergraduate ECE 1675 (4 credits)
  - Graduate ECE 2570 (3 credits)
    - Homework: 25%
    - Class participation: 10%
    - Midterm: 25%
    - Final exam: 40%

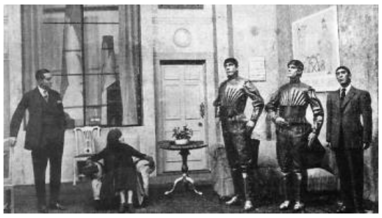
Don't miss 3 lectures without notifying

Course organization

- Times and places
- Instructors
- Reading material
- Evaluation
- Policies on distance learning
  - All students are required to attend the lectures during the lecture hours
  - Lectures will be recorded
  - If I experience a network connection problem during a lecture, please kindly wait for 15 min for me to get reconnected before you decide to leave the lecture

Introduction to robotics

- Defining robotics
  - A ***robot*** is an autonomous system which exists in the physical world, can sense its environment, and can act on it to achieve some goals

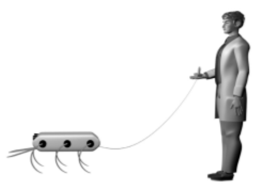


The word “robot” was popularized by the Czech playwright Karel Capek in his 1921 play *Rossum’s Universal Robots*

19

Introduction to robotics

- Defining robotics
  - A robot is an ***autonomous*** system which exists in the physical world, can sense its environment, and can act on it to achieve some goals



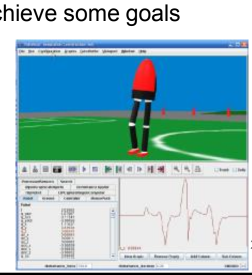
“An autonomous robot acts on the basis of its own decisions, and is not controlled by a human”

20

Spectrum of autonomy

Introduction to robotics

- Defining robotics
  - A robot is an autonomous system which exists in the ***physical world***, can sense its environment, and can act on it to achieve some goals



21

Not in simulation environment

Introduction to robotics

- Defining robotics
  - A robot is an autonomous system which exists in the physical world, can ***sense*** its environment, and can ***act*** on it to achieve some goals

Introduction to robotics

- Defining robotics
  - A robot is an autonomous system which exists in the physical world, can sense its environment, and can act on it to ***achieve some goals***
    - To do something useful for itself and/or others
    - Goals can be very simple or quite complex

Should have a purpose

Introduction to robotics

- Defining robotics
  - A robot is an autonomous system which exists in the physical world, can sense its environment, and can act on it to achieve some goals
  - Robotics is the study of robots
    - The study of robots' autonomous and purposeful sensing and acting in the physical world
    - An *interdisciplinary* branch of engineering and science that includes mechanical engineering, electronic engineering, information engineering, computer science, etc.

Introduction to robotics

- Defining robotics
- History of robotics
  - The practical possibility of robotics is based on developments in three fields: ***control theory***, cybernetics, and artificial intelligence
    - Without control theory, there would be no robotics
    - Control theory is the mathematical study of the properties of automated control systems (a control system is used to realize a desired output with desired performance)

25

Introduction to robotics

- Defining robotics
- History of robotics
  - The practical possibility of robotics is based on developments in three fields: control theory, ***cybernetics***, and artificial intelligence
    - Cybernetics is the scientific study of control and communication in the animal and the machine

Grey Walter's Tortoise (around 1940s)

26

Introduction to robotics

- Defining robotics
- History of robotics
  - The practical possibility of robotics is based on developments in three fields: control theory, cybernetics, and ***artificial intelligence***
    - The field of AI was officially "born" in 1956 at a conference held at Dartmouth University (participants included the most prominent researchers of the day: Marvin Minsky, John McCarthy, Allan Newell, Herbert Simon, etc.)

27

Introduction to robotics

- Defining robotics
- History of robotics
  - The practical possibility of robotics is based on developments in three fields: control theory, cybernetics, and ***artificial intelligence***
    - The field of AI was officially "born" in 1956 at a conference held at Dartmouth University
    - The conclusions of the meeting: in order for machines to be intelligent, … they will need
      - Internal models of the world
      - Search through possible solutions
      - Planning and reasoning to solve problems
      - Symbolic representation of information
      - Hierarchical system organization
      - Sequential program execution

28

Introduction to robotics

- Defining robotics
- History of robotics
  - The practical possibility of robotics is based on developments in three fields: control theory, cybernetics, and ***artificial intelligence***
    - The field of AI was officially "born" in 1956 at a conference held at Dartmouth University
    - The conclusions of the meeting
    - AI-inspired robots in the early days (60s~80s) were primarily focused on navigation and used *purely deliberative control*

seldom used in modern systems - algorithm takes a long time

Shakey the robot (in the late 1960s)

Introduction to robotics

- Defining robotics
- History of robotics
  - The practical possibility of robotics is based on developments in three fields: control theory, cybernetics, and ***artificial intelligence***
    - The field of AI was officially "born" in 1956 at a conference held at Dartmouth University
    - The conclusions of the meeting
    - AI-inspired robots in the early days (60s~80s) were primarily focused on navigation and used *purely deliberative control*
    - Later, several new robotics directions emerged and eventually organized into the types of robot control that we use today: *reactive control*, *hybrid control*, and *behavior-based control*

30

Introduction to robotics

- Defining robotics
- History of robotics
  - The practical possibility of robotics is based on developments in three fields: control theory, cybernetics, and artificial intelligence
  - All three fields are still very active in robotics research, and there have been a lot of interactions among them nowadays
    - Marriage between control theory and AI: control theory and AI used to focus on the lower-level and higher-level (nonphysical, unembodied cognitive) robot controls, respectively, but now there have been massive overlaps between them

31

Introduction to robotics

- Defining robotics
- History of robotics
  - The practical possibility of robotics is based on developments in three fields: control theory, cybernetics, and artificial intelligence
  - All three fields are still very active in robotics research, and there have been a lot of interactions among them nowadays
    - Marriage of control theory and AI
    - Biologically inspired control engineering

32

Biologically inspired robot control design

33

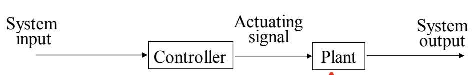
Introduction to control theory

- What is control system?
  - Generally speaking, a control system is a system that is used to realize a desired output or objective

34

Introduction to control theory

- What is control system?
  - Generally speaking, a control system is a system that is used to realize a desired output or objective
  - Open-loop control systems

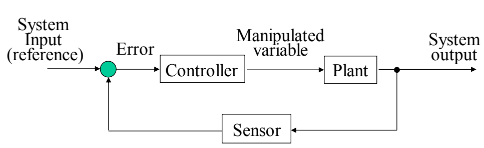


System/process under control

35

Introduction to control theory

- What is control system?
  - Generally speaking, a control system is a system that is used to realize a desired output or objective
  - Open-loop control systems
  - Closed-loop (or feedback) control systems

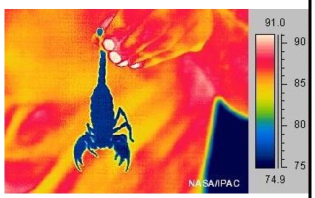


Measure current output

36

Introduction to control theory

- What is control system?
  - Generally speaking, a control system is a system that is used to realize a desired output or objective
  - Open-loop control systems
  - Closed-loop (or feedback) control systems
  - Examples of feedback control systems
    - Clock and heart
    - Temperature control



Clock - open loop (runs by itself and over time will eventually accumulate error)

Heart - closed loop (can be changed as needed - i.e. when exercising)

Introduction to control theory

- What is control system?
  - Generally speaking, a control system is a system that is used to realize a desired output or objective
  - Open-loop control systems
  - Closed-loop (or feedback) control systems
  - Examples of feedback control systems
  - Advantages and disadvantages of feedback
    - Feedback allows high performance in the presence of uncertainty
    - Feedback allows the dynamics of a system to be modified
    - Feedback may create instability

38

Feedback helps system to correct errors/disturbances in real time

Can use feedback to estimate internal state

More robust - don't have to know everything

Introduction to control theory

- What is control system?
- An example of control's application in under-actuated robotics
  - Honda's ASIMO vs. passive dynamic walkers vs. Boston Dynamics' Atlas

39

ASIMO - high gain control: reduces steady state error but is more unstable because of overshoot

Passive dynamic walker

Atlas - advanced control

Leg Laboratory - precursor to Boston Dynamics

Introduction to control theory

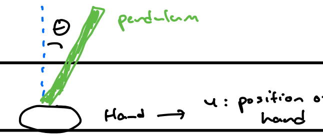
- What is control system?
- An example of control's application in aeronautics
- Another example: understanding fundamental limitations of feedback control facilitates the design of effective robot control and human-robot systems

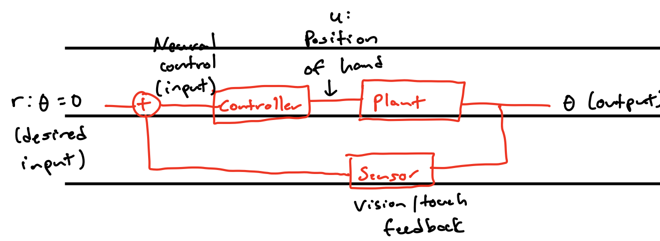
> A system with a right half plane pole p and a time delay T_d cannot be controlled unless the product pT_d is sufficient small. A simple rule of thumb is
> $$pT_d < 0.16.$$

in order for system to be controllable

Human control limitations in stabilizing an inverted pendulum

Goal: keep this balanced





Need to find equation linking u and θ

plant: $\frac{\theta(s)}{u(s)} = G(s) = \frac{s^2}{s^2 - \frac{g}{\ell}}$ ℓ: length of pendulum

(Laplace transform / transfer function) g: $9.8\ m/s^2$

Get roots of denom: $s^2 - \frac{g}{\ell} = 0$ $s_{1,2} = \pm\sqrt{\frac{g}{\ell}}$ unstable $p = \sqrt{\frac{g}{\ell}}$

T_d (known) ≈ 40 ms $= 0.04$ s

$pT_d < 0.16$ $\sqrt{\frac{g}{\ell}} \cdot 0.04 < 0.16$

$\sqrt{\frac{g}{\ell}} < 4$

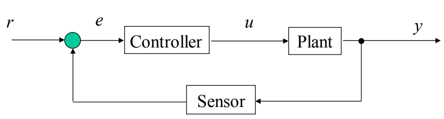
$\frac{g}{\ell} < 16$

$\ell > \frac{g}{16} \approx 0.6$ m

Length must be at least 60 cm for a human to do this

An example of control design: cruise control

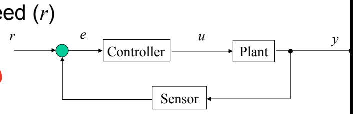
- Feedback control diagram



r: desired velocity
y: actual velocity
u: effort put into pedal/brake (can depend on what we choose)

An example of control design: cruise control

- Feedback control diagram
  - Objective: to make a car or a mobile robot drive at a desired, reference speed (r)
  - Plant:
    - Input: gas/brake (u)
    - Output: speed (y)
    - Model of dynamics (a mathematical relationship between the input and output):



$F = ma = m\frac{dy}{dt}$
(Newton's second law)

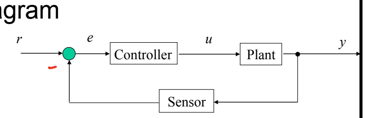
$F = cu$
(c = electro-mechanical transmission coefficient)

$$\boxed{\frac{dy}{dt} = \frac{c}{m}u}$$

F is proportional to u

An example of control design: cruise control

- Feedback control diagram
  - Objective
  - Plant $\boxed{\dfrac{dy}{dt} = \dfrac{c}{m} u}$



  - Error: $e = r - y$ (assuming the sensor gives a perfect measure of the speed)
  - Controller
    - The control signal should be a function of the error (e)
    - What properties should the control signal have?
      - Small e gives small u
      - It should not be "jerky" should be smooth
      - It should not depend on us knowing c and m exactly

An example of control design: cruise control

- Feedback control diagram
- Control design
  - Attempt 1: bang-bang control

$$\boxed{u = \begin{cases} u_{\max} & \text{if } e > 0 \\ -u_{\max} & \text{if } e < 0 \\ 0 & \text{if } e = 0 \end{cases}}$$

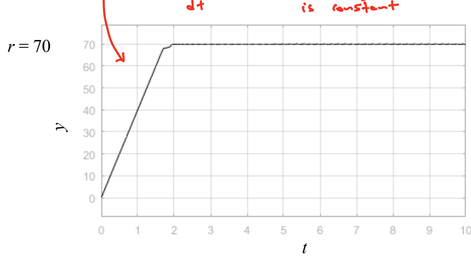
$e > 0$ $(r - y < 0$; $y < r)$ $\rightarrow$ push gas pedal to max

$e < 0$ $(r - y > 0$; $y > r)$ $\rightarrow$ push brake to max

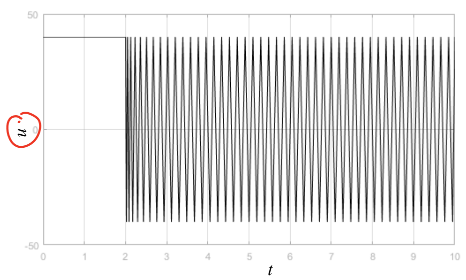
Straight line because no friction $\dfrac{dy}{dt} = \dfrac{c}{m} u$

$u = u_{max}$

so $\dfrac{dy}{dt}$ = constant meaning slope is constant



Bang-bang control



Bang-bang control
(problem: the controller over-reacts to small errors)

An example of control design: cruise control

- Feedback control diagram
- Control design
  - Attempt 1: bang-bang control
  - Attempt 2: proportional (P) control or regulation

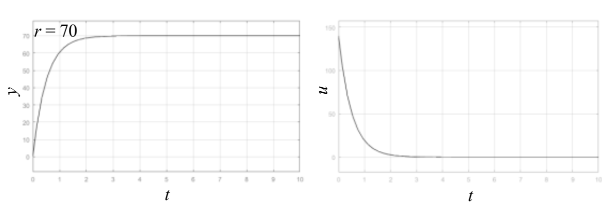
$$\boxed{u = ke}$$

- Small error yields small control signals
- Nice and smooth

(Previously):

$$\boxed{u = \begin{cases} u_{\max} & \text{if } e > 0 \\ -u_{\max} & \text{if } e < 0 \\ 0 & \text{if } e = 0 \end{cases}}$$

Steady state error $\rightarrow 0$



Proportional control

$u = ke$

$sY(s) = \frac{c}{m}u(s) \rightarrow \frac{Y}{u} = \frac{c}{ms}$

$\frac{dy}{dt} = \frac{c}{m}u \Longrightarrow \frac{Y(s)}{u(s)} = \frac{c}{ms}$

Transfer function from r to y:

$$\frac{y(s)}{r(s)} = \frac{k \cdot \frac{c}{ms}}{1 + k \cdot \frac{c}{ms}} = \frac{k \cdot \frac{c}{m}}{s + kc/m} = T(s)$$

DC Gain = 1 $\rightarrow$ y approaching steady state

DC Gain = $\lim_{s \to 0} T(s) = 1$, does not depend on k

Explains why SSE $\rightarrow 0$

Increasing K makes system converge faster

An example of control design: cruise control

- Feedback control diagram
- Control design
  - Attempt 1: bang-bang control
  - Attempt 2: proportional (P) control

$$\boxed{u = ke}$$

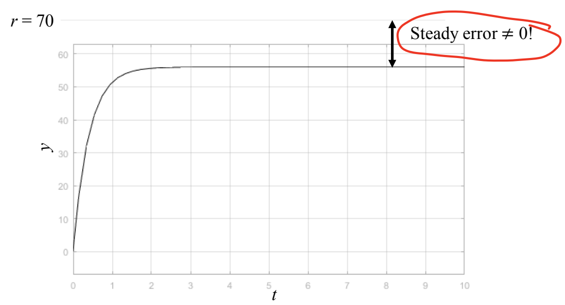
Now let us be more "real" by including a wind-resistance term in the model:

Transfer function is no longer an integrator

$$\boxed{\frac{dy}{dt} = \frac{c}{m}u - \gamma y}$$

Damping, which is proportional to speed

49



Proportional control
(for the plant model considering wind resistance)

$$\boxed{\frac{dy}{dt} = \frac{c}{m}u - \gamma y}$$

50

Use PI control

$$\frac{dy}{dt} = 0 = \frac{c}{m}u - \gamma y = \frac{c}{m}k(r - y) - \gamma y$$

$$\Downarrow$$

$$y_{ss} = \frac{ck}{ck + m\gamma}r$$

$$\Downarrow$$

$$e_{ss} = r - y_{ss} = \frac{m\gamma}{ck + m\gamma}r$$

Calculation of the steady-state error e_{ss}

51

An example of control design: cruise control

- Feedback control diagram
- Control design
  - Attempt 1: bang-bang control
  - Attempt 2: proportional (P) control
  - Attempt 3:

$$\boxed{u = ke + \gamma \frac{m}{c} y}$$

$$\frac{dy}{dt} = 0 = \frac{c}{m} u - \gamma y = \frac{c}{m} k(r - y) + \gamma y - \gamma y \;\Rightarrow\; y_{ss} = r$$

52

An example of control design: cruise control

- Feedback control diagram
- Control design
  - Attempt 1: bang-bang control
  - Attempt 2: proportional (P) control
  - Attempt 3:

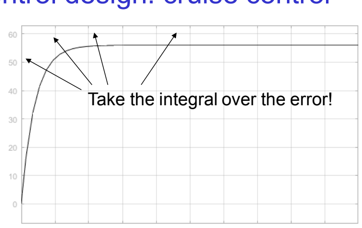
$$\boxed{u = ke + \gamma \frac{m}{c} y} \;\Rightarrow\; y_{ss} = r$$

However, we do not have ***robustness***, as we do not know m, c, and γ!

53

An example of control design: cruise control

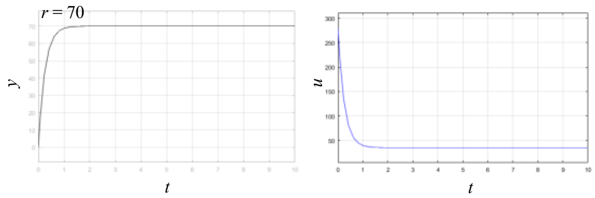
- Feedback control diagram
- Control design
  - Attempt 1: bang-bang control
  - Attempt 2: P control
  - Attempt 3: $u = ke + \gamma \frac{m}{c} y$



  - Attempt 4: proportional-integral (PI) control

$$\boxed{u(t) = k_P e(t) + k_I \int_0^t e(\tau) d\tau}$$

54



PI control

An example of control design: cruise control

- Feedback control diagram
- Control design
  - Attempt 1: bang-bang control
  - Attempt 2: P control
  - Attempt 3: $u = ke + \gamma \frac{m}{c} y$
  - Attempt 4: PI control
  - Attempt 5: proportional-integral-derivative (PID) control

$$u(t) = k_P e(t) + k_I \int_0^t e(\tau) d\tau + k_D \frac{de(t)}{dt}$$

An example of control design: cruise control

- Feedback control diagram
- Control design
  - Attempt 1: bang-bang control
  - Attempt 2: P control
  - Attempt 3: $u = ke + \gamma \frac{m}{c} y$
  - Attempt 4: PI control
  - Attempt 5: proportional-integral-derivative (PID) control

P: medium-rate responsiveness $P \propto e$

I: slow-rate responsiveness; zero e_{ss}; disturbance rejection; may cause oscillations and instability $P \propto \int_0^t e(\tau) d\tau$

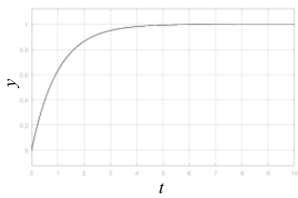
D: fast-rate responsiveness; sensitive to noise $P \propto \frac{de(t)}{dt}$

$$u(t) = k_P e(t) + k_I \int_0^t e(\tau) d\tau + k_D \frac{de(t)}{dt}$$

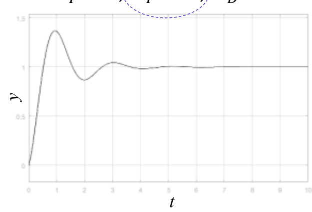
By far the most used low-level controller!

$$\frac{dy}{dt} = \frac{c}{m}u - \gamma y, \qquad \text{where } c = 1, m = 1, \gamma = 1, r = 1$$

$k_P = 1,\ k_I = 1,\ k_D = 0$



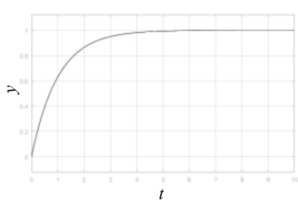
$k_P = 1,\ k_I = 10,\ k_D = 0$



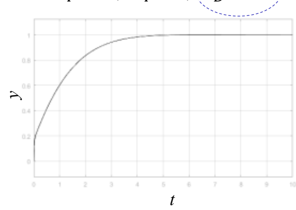
58

$$\frac{dy}{dt} = \frac{c}{m}u - \gamma y, \qquad \text{where } c = 1, m = 1, \gamma = 1, r = 1$$

$k_P = 1,\ k_I = 1,\ k_D = 0$



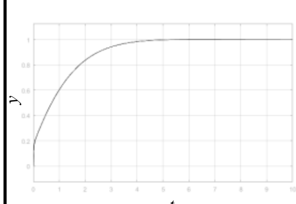
$k_P = 1,\ k_I = 1,\ k_D = 0.2$

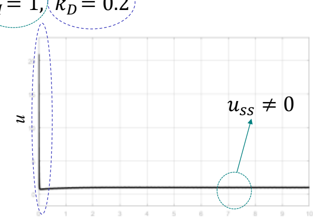


59

$$\frac{dy}{dt} = \frac{c}{m}u - \gamma y, \qquad \text{where } c = 1, m = 1, \gamma = 1, r = 1$$

$k_P = 1,\ k_I = 1,\ k_D = 0.2$





60

References (I)

- M. Egerstedt, Lecture Notes for Control of Mobile Robots, Georgia Institute of Technology, 2016.
- M. Mataric, The Robotics Primer, MIT Press, 2007.
- R. A. R. Picone, Lecture Notes for ME 454/554 Robotics and Automation, Saint Martin's University, 2017.
- K. J. Astrom and R. M. Murray, Feedback Systems: An Introduction for Scientists and Engineers, 2010.
- C. L. Phillips and R. D. Harbor, Feedback Control Systems, 4th Edition, Prentice Hall, 2000.
- J. Pratt and B. Krupp, "Design of a bipedal walking robot," in Proceedings of SPIE, doi: 10.1117/12.777973, April 2008.
- R. Tedrake, Lecture Notes for 6.832 Underactuated Robotics, MIT, 2018.
- https://agogodrone.com/
- http://coolcosmos.ipac.caltech.edu/image_galleries/ir_zoo/coldwarm.html
- https://en.wikipedia.org/wiki/Robot

61

References (II)

- https://project.dke.maastrichtuniversity.nl/SwarmLab/
- https://web.stevens.edu/vinjamurilab/research.html
- https://world.honda.com/ASIMO/
- https://www.bostondynamics.com/atlas
- https://www.eucognition.org/index.php?page=passive-dynamic-walkers
- https://www.generationrobots.com
- https://www.motoman.com/blog/topic/mobile-robotics
- https://www.scientificamerican.com/article/walking-the-dinosaur/
- https://www.smashingrobotics.com/overview-of-commercially-available-professional-robotic-manipulators-part-2/

62