Control System Design - A Perspective

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1. Introduction
2. Integrated System and Control Design
3. Control Principles
4. Requirements and Methods
5. Summary

Theme: Many things to think about.

Introduction

- Control is a rich field
  - Many domains (process control, power, aero, robotics, telecom, ...)
  - A rich collection of methods
  - Mass production vs tailor-made
- Important to understand the process and the requirements
- Design always involves many criteria, trade-offs and compromises
- Most design methods (theories) only capture a few
- Necessary to analyze, simulate and validate
- Theory and design have different goals (Math versus carpentry)
- Motto: Simple is beautiful
- A cardinal sin: To believe that the process is given!

What is Control?

Important to have some feel for the full picture

- Architecture

  Process, sensors, actuators, communication, computers

- Requirements
- Modeling and simulation
- Control design
- Implementation

  CPU, sensors, actuators, MMI, platforms, software

- Validation, verification
- Commissioning (tuning)
- Operation (diagnostics, fault diagnosis)
- Upgrade and reconfiguration

Important to be aware of the larger picture!

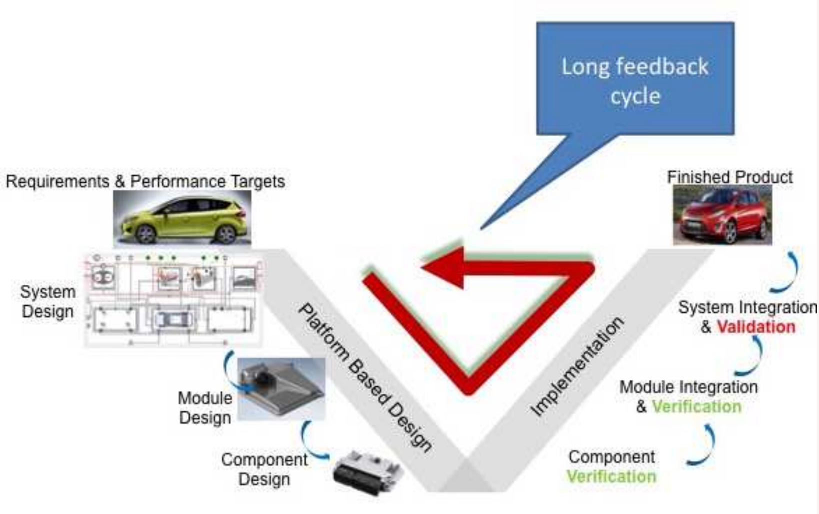
Extremely Wide Range

- Number and variety of systems
- Life time of systems/processes
- Available design effort

Example

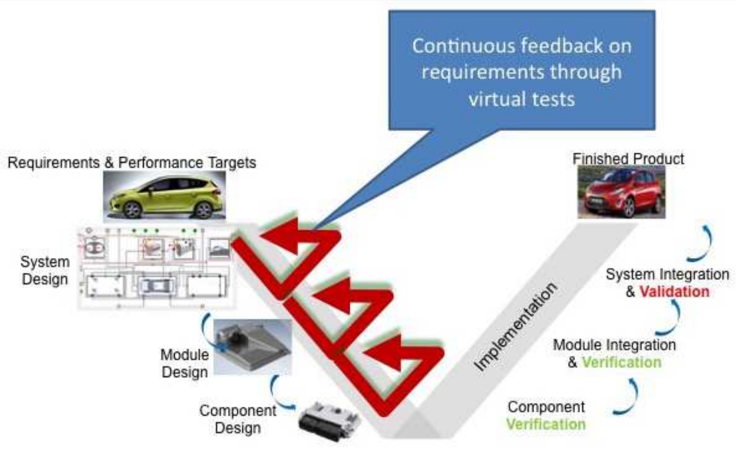
- Cell phones
- Physics experiments, CERN, MAX, ESS
- Automotive
- Aircraft
- Airconditioning system for aricrafts

Model Based Design 1 - Open Loop



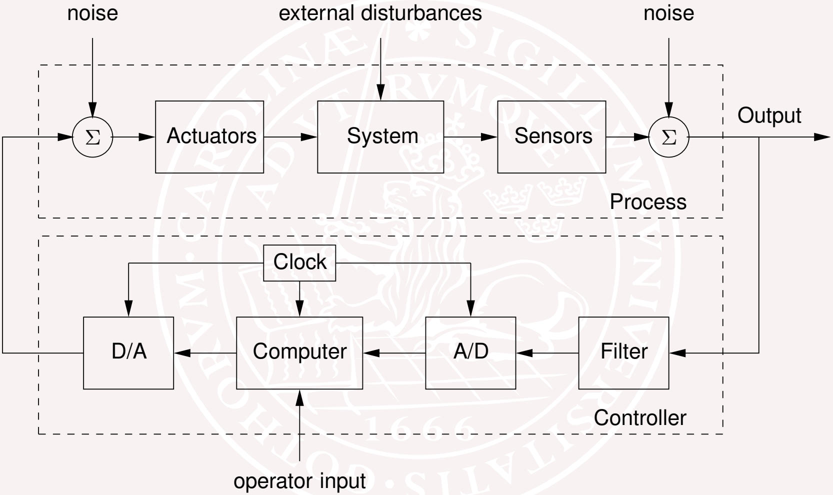
Final test comes late

Model Based Design 2 - Closed loop



Models are uses as virtual systems SIL & HIL
Errors caught early, very useful when changes are made.

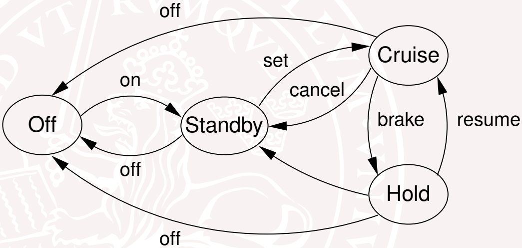
Implementation - Computer Control



Sense, reflect (compute) and act

The Human Machine Interface - Mode switches

What happens when the driver hits the break or accelerates?



Control systems consist of: controllers, finite state machines and logic.

We should do a better job to cover this!!

Continuous or Discrete Time

- Important issues that must be considered
- Personal experiences:

  FOA/KTH 55-60, IBM 60-65, LTH/Saab JA37 70-75, UTC 2008-
- There are sampled versions of all continuous methods
- You must know about discretization issues even if they are not covered in this course
- Equations simpler in continuous time
- Simple discretizations work well if computing time is not critical
- There are always situations where computing time is very critical

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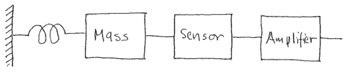
Integrated System and Control Design

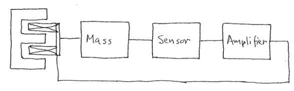
By adding sensors, actuators and feedback to a process a system has the potential for dramatic improvements because it gives the designer extra degrees of freedom. Control principles are the basic concepts for system design. There are many examples.

- Process control - keep variables constant
- Servo systems - make variables change in a prescribed manner following commands
- Force feedback - dramatic improvements of sensors
- Ships, aircrafts and birds
- Inertial navigation
- Supply chain management

Force Feedback

- Classic idea with tremendous impact
- Introduction of actuation and feedback in sensors was a game changer in instrument design





Open loop, all components matter

Bandwidth $\omega_b = \sqrt{k/m}$

Sensitivity = k_a/k

Invariant $\omega_b^2 S = k_a/m$

Closed loop, actuator only critical element

Bandwidth depends on feedback system

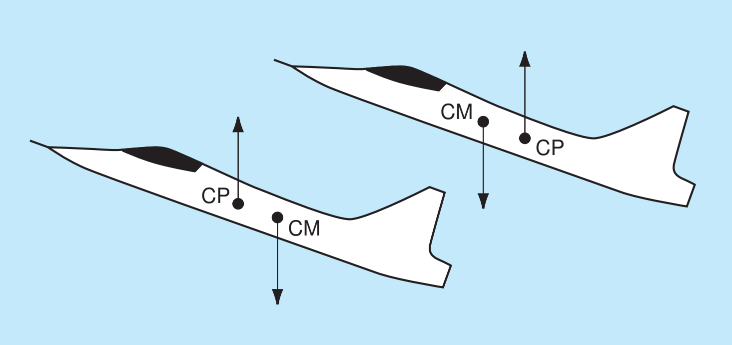
Error signal also useful!

Automobiles

Introduction of the Lambda sensor and feedback to the engine made it possible to satisfy the California emission law. A nice side effect was the microprocessor. Once a computer was in the car there were many natural developments, all involved additional sensing and feedback.

- Cruise control
- Adaptive cruise control
- Traction control
- Collision avoidance
- Lane guidance
- Platooning
- Autonomous cars

JAS Gripen



- Advantages of unstable aircraft
- Unstable operating conditions
- Rate saturation due to hydraulics

Birds

John Maynard Smith, *The Importance of the nervous system in the evolution of animal flight.* **Evolution**, 6 (1952) 127-129.

The earliest birds pterosaurs, and flying insects were stable. This is believed to be because in the absence of a highly evolved sensory and nervous system they would have been unable to fly if they were not. To a flying animal there are great advantages to be gained by instability. Among the most obvious is manoeuvrability, it is of equal importance to an animal which catches its food in the air and to the animals upon which it preys. It appears that in the birds and at least in some insects the evolution of the sensory and nervous systems rendered the stability found in earlier forms no longer necessary.

Inertial Navigation - Schuler Tuning

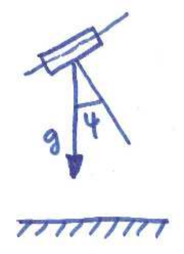
Draper: MIT Instrumentation Laboratory

Idea: integrate acceleration twice!

Gamov: Vertical, Vertical, Who's got the Vertical?

Longitudinal position error with constant gyro drift

$$\ddot{e}_x = g\psi, \qquad \psi = \omega_0 t, \qquad e_x = \frac{g\omega_0}{6} t^3$$



If $\omega_0 = 1°/h = 4.8 \times 10^{-6}$ [rad/s], $t = 3600$s then $e_x = 370$ km

Drift rates must come down to $0.01°$/h. Azimuth gyro drift less critical

- Strong scepticism from George Gamov and others in 1940s
- Draper's coup: Classified conference, Gamov invited, but did not come.

The Idea (1923)

Make a pendulum and increase its apparent moment of inertia with acceleration feedback

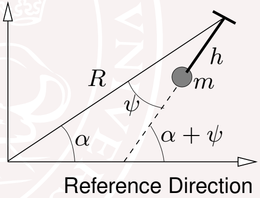
- Avoid closing the Schuler loop through the gimbals
- Schuler loop requires only low frequencies (84 min)

Equations of motion:

$$J\frac{d^2\theta}{dt^2} = -mgh\psi + mRh\frac{d^2\alpha}{dt^2} + u$$

$$u = -k\frac{d^2\theta}{dt^2}$$

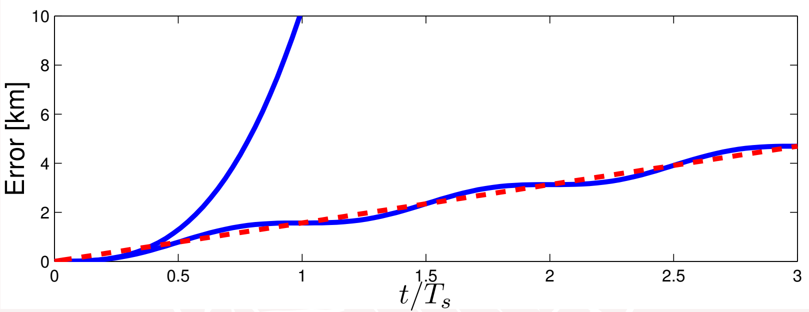
$$(J+k)\frac{d^2\theta}{dt^2} = -mgh\psi + mRh\frac{d^2\alpha}{dt^2}$$



$$(J+k)\frac{d^2\psi}{dt^2} + mgh\psi = (mRh - J - k)\frac{d^2\alpha}{dt^2}$$

Schuler Tuning - Error Growth

Gyro drift 0.01° per hour



$$e(t) = \frac{g\omega_0}{6}t^3, \;\; e(t) = R\omega_0\Big(t - \frac{1}{\omega_s}\sin(\omega_s t)\Big), \;\; \omega_s = \sqrt{g/R} \quad (T_s = 84\text{min})$$

Recognition from MIT

Indication of the vertical with a pendulum

Physical Realizability

The condition stated by Eq. (4.1) is not physically realizable because of the small pivot-centre-of-mass separation. After 1923 apparently no attempt was made to synthesize a Schuler-tuned pendulum electromechanically, although recently such a scheme has been proposed by Åström and Hector.[6] The method by which vertical indication is accomplished today was, to the authors' knowledge, first described by Reisch in 1945[7] and is the subject pursued in the following chapter, with the kinematic relationships developed here as a basis.

W. R. Markey and J. Hovorka *The Mechanics of Intertial Position and Heading Indication*, Wiley, New York 1961

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Control Principles

Overriding principles for controlling a system

Traditional schemes:

- Regulation
- Servoing - track following
- Stabilization
- Shaping behavior
- Extremal seeking

  Force feedback
  Compliance control
  Collision avoidance
  Path planning

High level control principles

- No systematic approach illustrativ examples

Stabilize

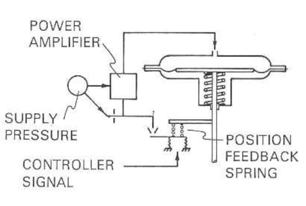
- Airplanes

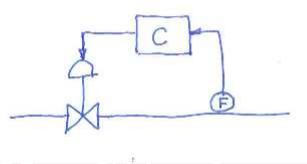
  The Wright brothers

  Process and control design
- Ships

  Minorsky 1922: It is an old adage that a stable ship is difficult to steer.
- Bicycles
- Segway
- Missiles
- Exotherm reactors
- Nuclear reactors

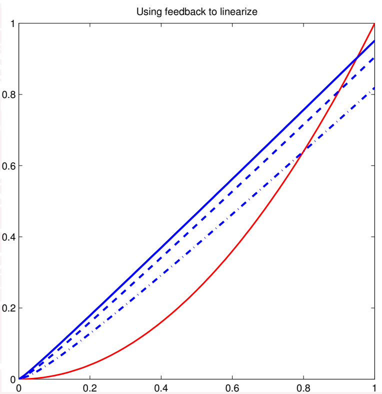
Shaping Behavior - Process Control





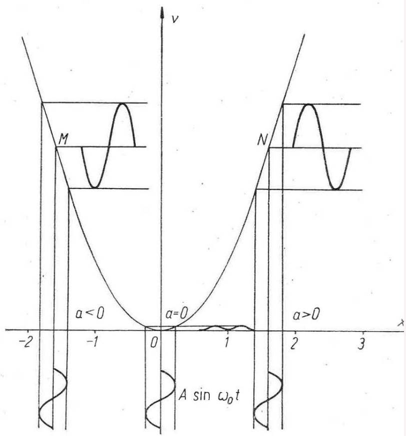
Valve positioner makes valve position proportional to control signal independent of friction and spring nonlinearities

Local feedback from flow measurement makes flow proportional to setpoint independent of valve characteristic



Extremal Seeking - Optimization

- Draper-Lee Optimize jet engine performance
- Bacteria searching for light or food
- Optimize production rate or quality



Perturb input orrelate with output

Shaping Behavior - Impedance Control and Haptics

Impedance control

Make a robot arm behave like a soft spring with adjustable null force position and adjustable spring coefficient.

Haptics

Provid a joy stick with an actuator that generates torques that reflect an externally generated torque.

$$J\frac{d^2\theta}{dt^2} = T_{external} + T_{fb}$$

$$T_{fb} = k_p(\theta_0 - \theta) - k_d\frac{d\theta}{dt} - k_a\frac{d^2\theta}{dt^2}$$

$$(J + k_a)\frac{d^2\theta}{dt^2} + k_d\frac{d\theta}{dt + k_p\theta} = k_p\theta_0 + T_{external}$$

Look at old motordrive!

Examples of High Level Control Principles

Very important but unfortunately no general principles available.

- Raiberts hopper
- HVDC transmission Hugo Lamm
- Flow control and supply chains
- Energy control pendulum swingup
- Grundelius anti-sloshing controller
- Proportional navigation

Raibert's Hopper

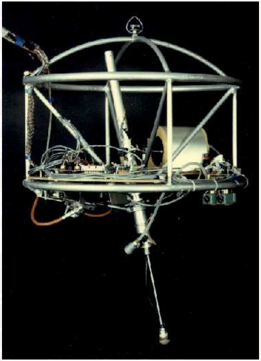
Three control problems

- Attitude control
- Hopping
- Forward motion

    Loading
    Compression
    Thrust
    Unloading
    Flight

Control principle: footprint

Raibert 83-84

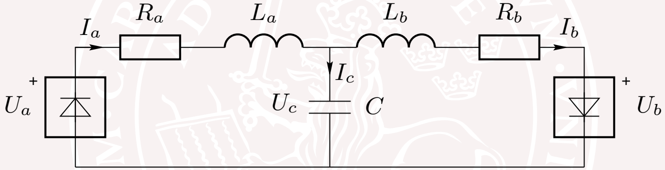


Show video

www.ai.mit.edu/projects/leglab/robots/3D_hopper/3D_hopper.html
www.robothalloffame.org/08inductees/raibert.html

HVDC Transmission System

- Pioneered by ASEA (Uno Lamm), ABB still very strong
- A key component in smart grids



Large power and fast power changes

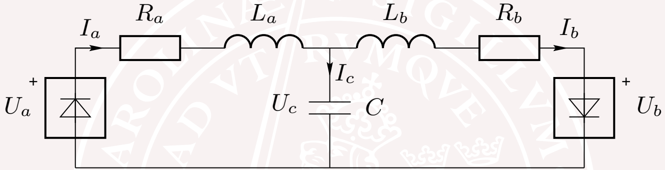
Communications cannot be trusted!

Decentralized control!

Find a control principle that accomplishes that safely

Think!

HVDC Transmission System



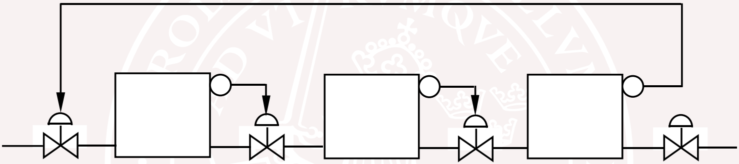
Shape static $I - V$ characteristic of source and sink (Uno Lamm's idea)

- Control rectifier (sender) so that it behaves as a voltage source
- Control inverter (receiver) so that it behves as a current sink

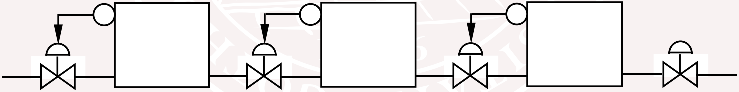
Actuator saturations important

Flow Control and Supply Chains

Control in the direction of the flow



Control in the direction opposite to the flow



Energy Control

Pendulum swing-up

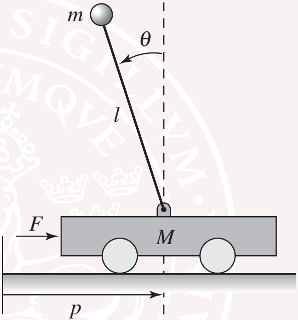
Equations of motion

$$\ddot{\theta} = \sin\theta + u\cos\theta$$

Energy

$$E = \cos\theta + \frac{1}{2}\dot{\theta}^2 - 1$$

$$\dot{E} = u\dot{\theta}\cos\theta$$

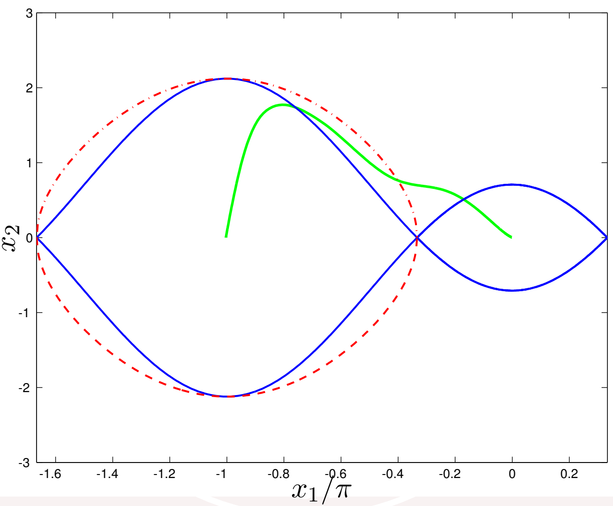


Energy is driven to zero with the strategy

$$u = -E\dot{\theta}\cos\theta, \qquad \dot{E} = -\left(\dot{\theta}\cos\theta\right)^2 E$$

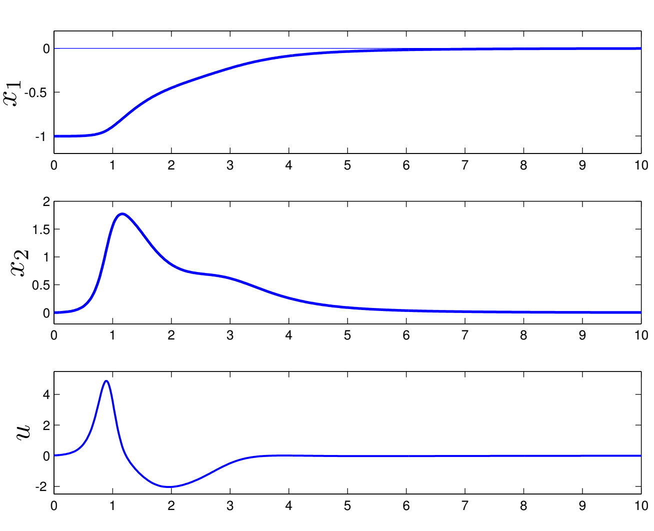
Easier to control energy than to control position!

Energy Shaping

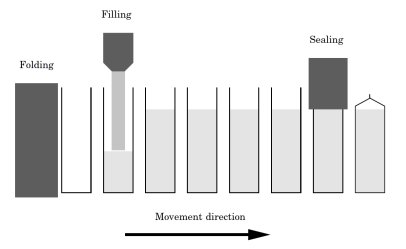


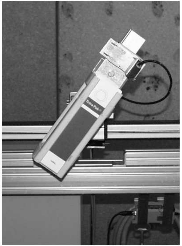
Continuous control laws, see Automatica 2000

Trajectories



Mattias Grundelius 2001, Anti-sloshing Design





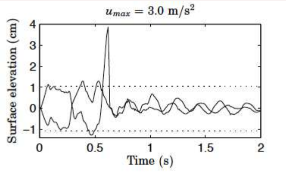
- Unit operation in Tetra Pak, avoid liquid to reach glue zone
- Time optimal control: problems with model imperfections
- Add small extra time, minimize control energy: worked very well

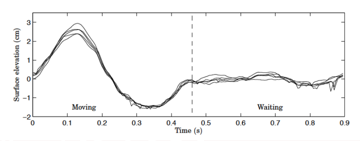
One way of making the acceleration reference smoother is to solve an minimum energy problem instead. The cost function

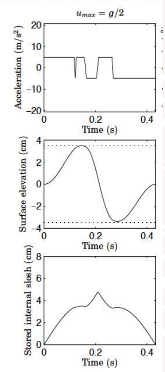
$$J = \int_0^{T_{opt}+\Delta} u^2(t)\, dt$$

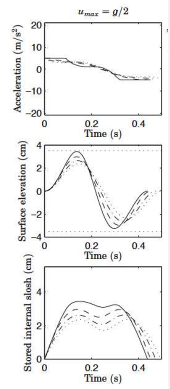
is minimized subject to the constraints C1–C4 and the slosh model in (3.39). Here T_{opt} is the movement time from the solution of the minimum time problem and Δ is the extra time allowed for the movement.

Minimum time(left) vs minimum energy(right)



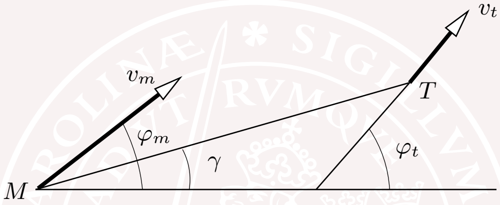






Implemented in Tetra Pak system

Proportional Navigation

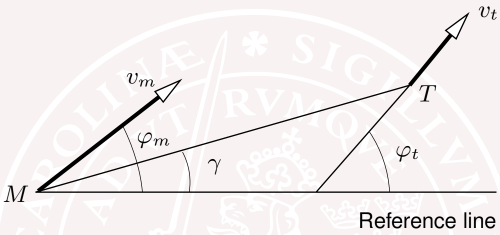


Dynamics:

$$\frac{dr}{dt} = v_t \cos(\varphi_t - \gamma) - v_m \cos(\varphi_m - \gamma) = -v_c$$
$$r\dot{\gamma} = v_t \sin(\varphi_t - \gamma) - v_m \sin(\varphi_m - \gamma)$$

Find a control strategy that is simple to implement
Fourth order state, what information is required?
Make minimal assumptions about target motion!

Proportional Navigation ...



Dynamics

$$\frac{dr}{dt} = v_t \cos(\varphi_t - \gamma) - v_m \cos(\varphi_m - \gamma) = -v_c$$
$$r\dot{\gamma} = v_t \sin(\varphi_t - \gamma) - v_m \sin(\varphi_m - \gamma)$$

Control law (compare with collision avoidance when sailing)

$$\frac{d\varphi_m}{dt} = k\frac{d\gamma}{dt}, \qquad \textit{Rate of change of line-of-sight}$$

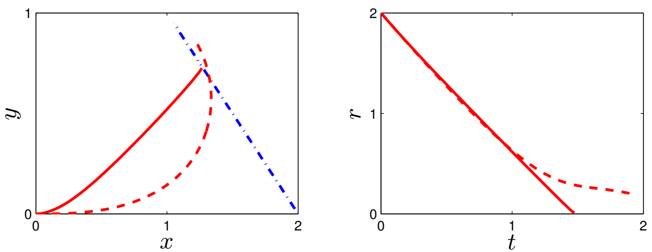
Proportional Navigation ...

Linearize for small $\varphi_m - \gamma$ and introduce $\omega = \dot{\varphi}_m$ gives

$$\frac{d\omega}{dt} = \Big(2 - \frac{kv_m}{v_c}\Big)\frac{v_c}{r}\omega$$

Time-varying linear system. Stable if $k > 2v_c/v_m$.

Comparison with simple pursuit when normal acceleration limited. Simple pursuit (dashed) does not hit the target!



Control Principles Summary

- Traditional: servo, regulate, stabilize, shape behavior
- High level principle have been revolutionary
- High level principles are based on understanding the system
- Seldom talked about
- Not aware of any good overviews but it is on my to-do list
- There are many more than discussed above

  den Hartog's vibration damper
  Sky hook damper
  Force feedback for instrumentation
  Ackermann's decoupling point
  Ship steering - steer radius instead of steer angle
  Control of concentration and levels
  Walking robot
  Snake robot

- Good topic for mini projects

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Theme: Many things to think about.

Requirements Drive Design

Typical requirements

- Performance
  - Load disturbance attnuation
  - Measurement noise injection
  - Command signal following
  - Optimality
- Robustness
  - Sensitivity to process variations
- Ease of use

Important to understand qualitatively and quantitatively how requirements are influenced by the design choices, the controller and its parameters

Some Design Methods

Purpose

- Insight and understanding
- Result in controllers

Major methods

- Loopshaping
- Quantitave Feedback Theory
- Poleplacement
- PID Control
- Linear Quadratic Control
- H_∞ Control

Auxiliary methods

- The root locus method

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