TÉCNICO LISBOA

Controlo em Espaço de Estados

2019/2020

João Miranda Lemos

Professor Catedrático

Faculty

João Miranda Lemos

(Theoretical lectures, course coordinator)

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Pedro Batista (Lab and Problems)

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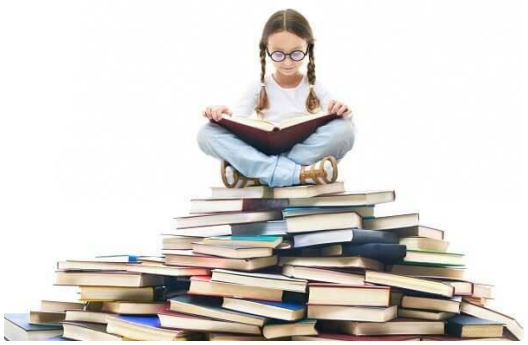
Where do I study from?



- Slides in 4 parts (see Fénix)
- Problems (see Fénix)
- Lab guide (see Fénix)
- Livro: João Miranda Lemos, Controlo no Espaço de Estados, IST Press, 2019. Colecção Ensino de Ciência e Tecnologia nº 64. Contém todo o curso, incluindo problemas.

- Franklin, Powell, Emami-Naeini. *Feedback Control of Dynamic Systems* (chaps. 7, 9) Non-exhaustive

Sincronização entre o livro de texto e os slides

Cada uma das secções dos slides está marcada com

[JML-BookCEE] pág. Início – pág fim

Ou com os problemas relevantes para essa secção, que devem ser lidas/resolvidos a seguir à aula correspondente.

Evaluation and grading

- Theory
  - 2 tests (strongly recommended) or **1** exam
  - Approval: Theory grade (average of tests or exam) minimum of 9,3
  - There is no minimum grade in each individual test.
  - If approved by tests, may improve the theory grade in the exam
- Laboratory
  - 1 work, report in **groups of 4** (also 3), grades individual by student
- Final grade
  - *0,7T+0.3L* Above 17 must be confirmed in a special exam

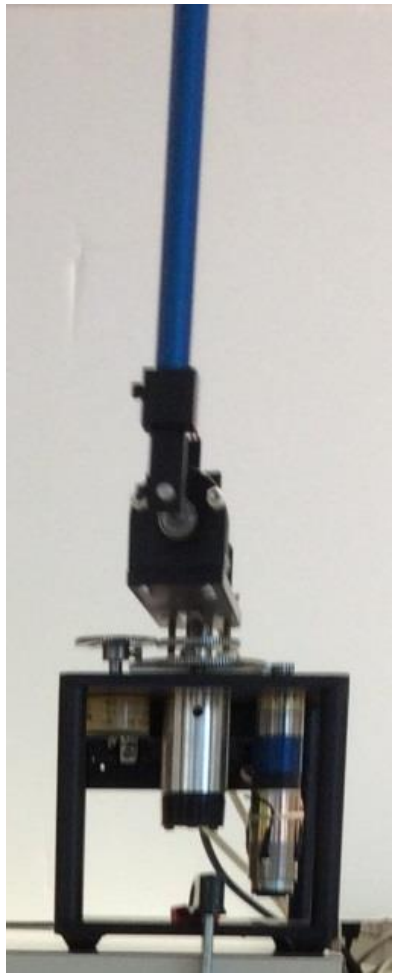
Laboratory

Objective: Design and test a state feedback controller to equilibrate an inverted pendulum. https://youtu.be/wpV_A8o3YJQ

Emphasis on the design of computer controlled systems with experimental verification – ***Cyber Physical Systems***

1. Design an optimal state feedback controller based on a given model. MATLAB
2. Test in simulation. Review the design. SIMULINK
3. Test on the real plant. Evaluate. Improve. SIMULINK

MATLAB is increasingly popular in industry to develop initial versions of new ideas.



Why have you chosen this course?

Mas afinal, esta é, ou não é, a reunião do Sindicato dos Padeiros?

After all, is this, or is it not, the meeting of the Baker's Union?

A striking example: Humanoid robot control

The Atlas humanoid robot by Boston Dynamics

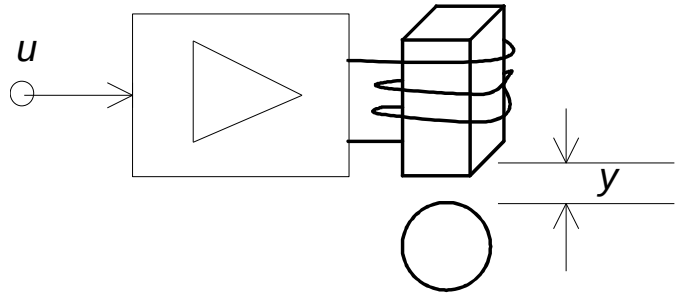
https://www.youtube.com/watch?v=_sBBaNYex3E

Uses model based nonlinear control techniques.

Other high performance humanoid robots based on optimal control.

CEE introduces these techniques.

The state model



Input/output model (differential equation or transfer function): $\frac{d^2y}{dt^2} = u$

Alternative: Two first-order differential equations (state model)

$$x_1(t) = y(t)\ ,\ x_2(t) = \dot{y}(t) \qquad \begin{cases} \frac{dx_1}{dt} = x_2 \\ \frac{dx_2}{dt} = u \end{cases}$$

State of a system: A set of variables such that, if you known them at an instant, together with the set of external forces that will act on the system, you can compute their values for all future time.

The state variables satisfy a set of 1st order differential equations known as the state model. Example in the linear case:

$$\frac{dx}{dt} = Ax + Bu \quad \text{(Model of dynamics and actuators)}$$

$$y = Cx \quad \text{(Sensor model)}$$

We will study the non-linear case as well.

Leitura sugerida

[JML-CEE2019] pp. 3 – 17

Questões e problemas pp. 21 - 23

Course objective

Study of state model methods for control systems analysis and design.

Syllabus

1. Linear state model analysis (model conversion, time response, structural properties – Controlability, observability).
2. Linear Controller design based on state variable feedback and state estimation with observers.

1st test ==========

3. Stability and controller design for nonlinear systems.
4. Optimal Control design using Pontryagin's maximum principle.

2nd test

What are the main new things to learn in this course?

- A new model (state model, linear and nonlinear)
- A new technique to study stability (Lyapunov's direct method)
- New controller design methods
  - Pole placement by linear state feedback (including Kalman filter)
  - Non-linear control
  - Optimal control (Pontryagin's Maximum Principle)
  - Multivariable control
  - Adaptive control (learn the model while the controller operates)

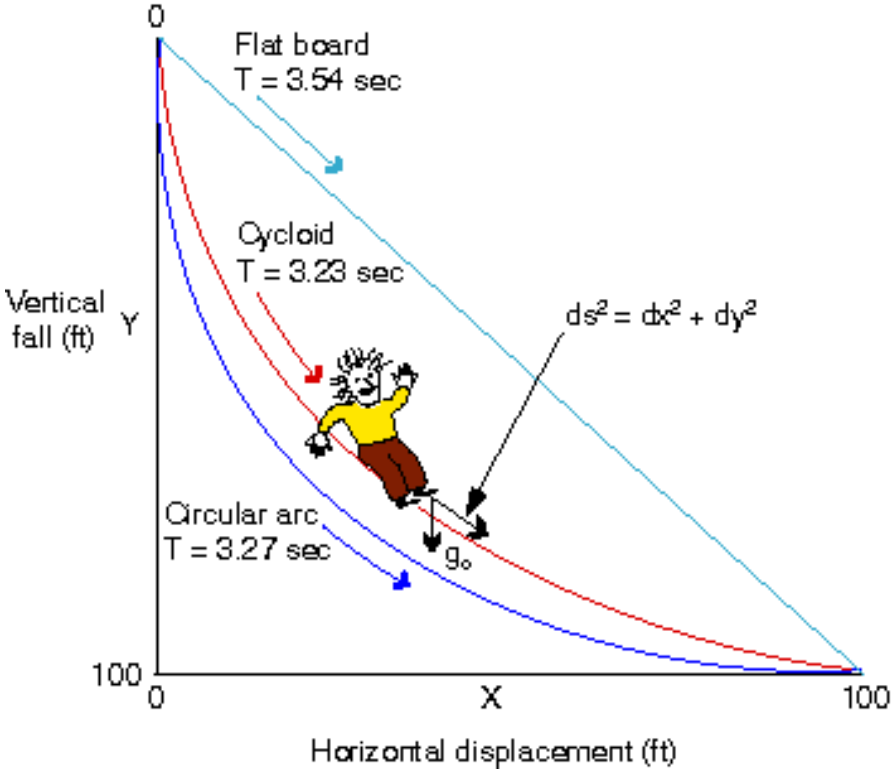
Where did these ideas came from?

Aleksandr Lyapunov 1857-1918 *Stability of nonlinear systems*

Rudolph Kalman 1930-2016 *K-B. filter. State model in Control*

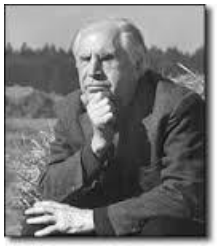
Johann Bernouilli (1667-1748) and the brachistochrone

What is the curve of fastest descent when sliding between (0,0) and the final point?



L. Euler 1707-1783 *Variational Calculus. Euler-Lagrange equation*

Joseph-Louis Lagrange 1736-1813 *Analytical Mechanics*



Lev Pontryagin 1908-1988 *Principle to solve optimal control problems*

Biographic notes in the text book

Biographic sketches of the above personalities can be seen in the textbook [JML-CEE2019]:

Lyapunov – p. 339

Kalman – pp. 147,148

Johann Bernouilli – pp. 392-393

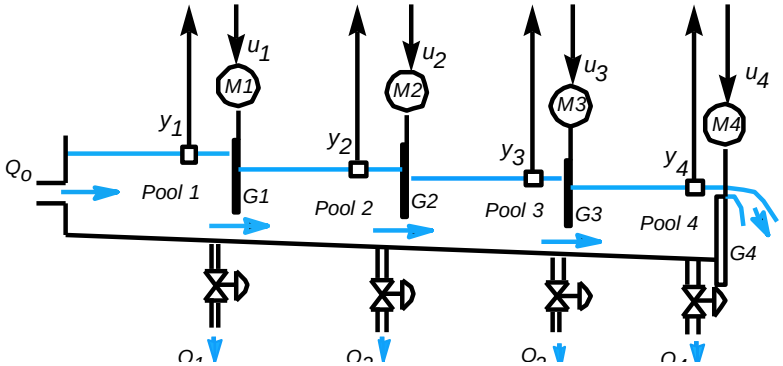
Euler – pp. 401-404

Lagrange – pp. 405, 406

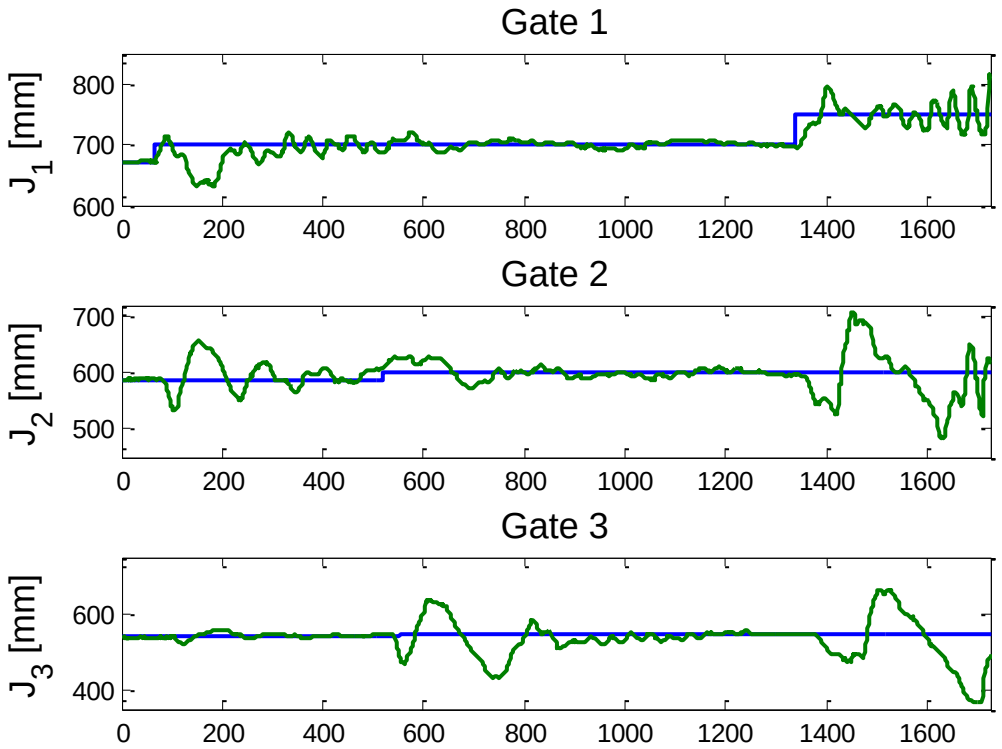
Pontryagin – pp. 407-408

Anastácio da Cunha – pp. 105-107

Examples of engineering problems that you can tackle with the techniques studied in CEE: Water delivery canal

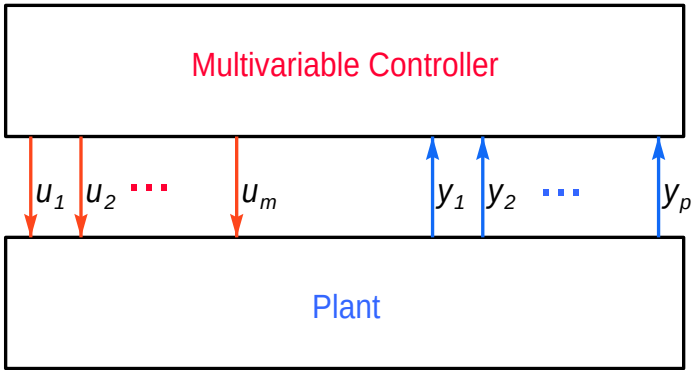


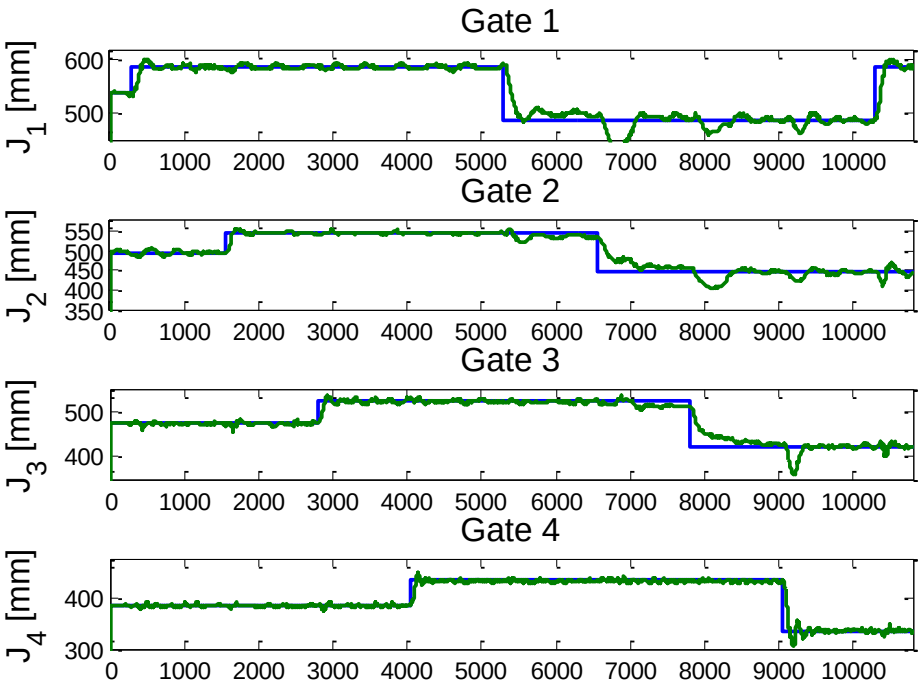
Isolated PID's (no coordination)



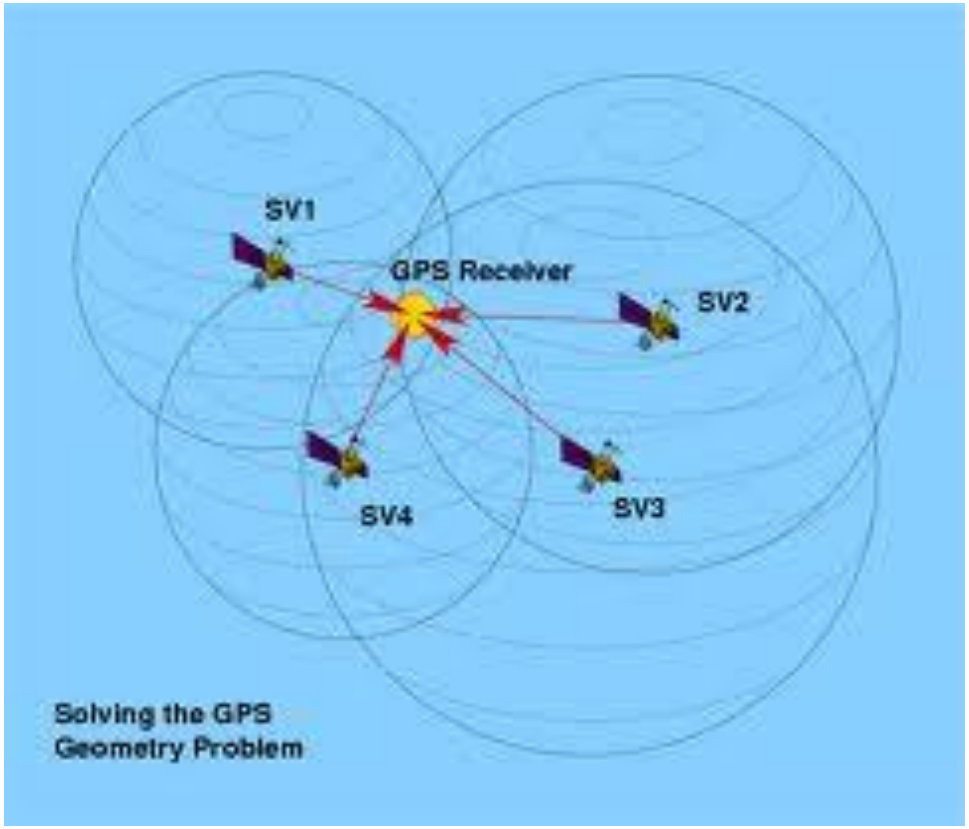
Canal optimal multivariable state feedback control

J. M. Lemos and L. F. Pinto (2012). Distributed Linear-Quadratic Control of Serially Chained Systems -- Application to a Water Delivery Canal. IEEE Control Systems Mag., 32(6):26-38.





State estimation: Localization using GPS

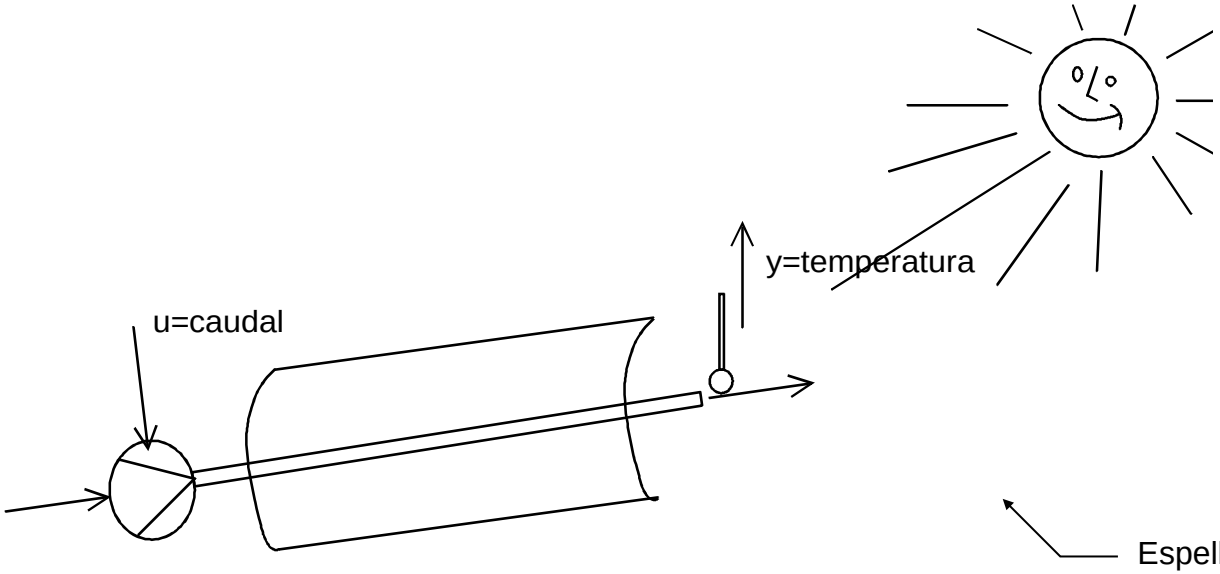


$$\frac{dx}{dt} = f(x) \quad y = h(x)$$

Estimate x using the measures of y .

- Observers

Parabolic trough solar thermal fields



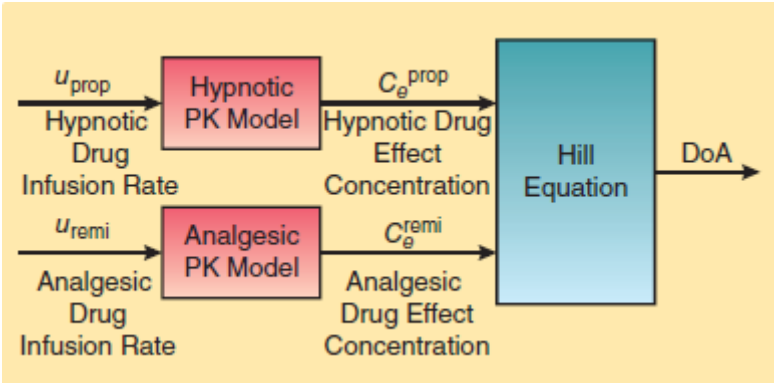
Keep the outlet temperature constant despite changes in solar radiation.

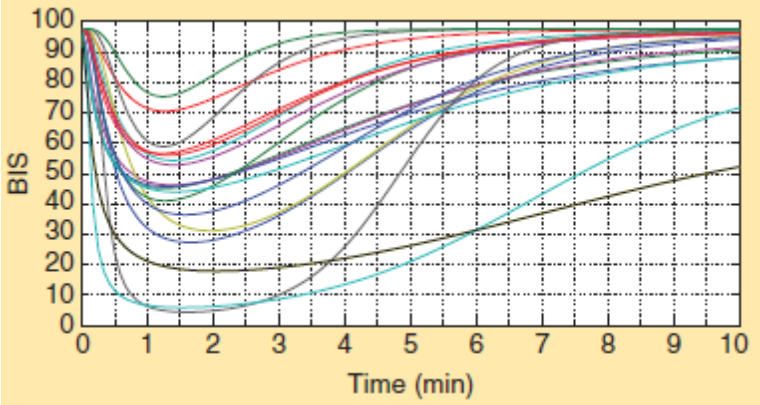
An example of a nonlinear system to be tackled in the course.

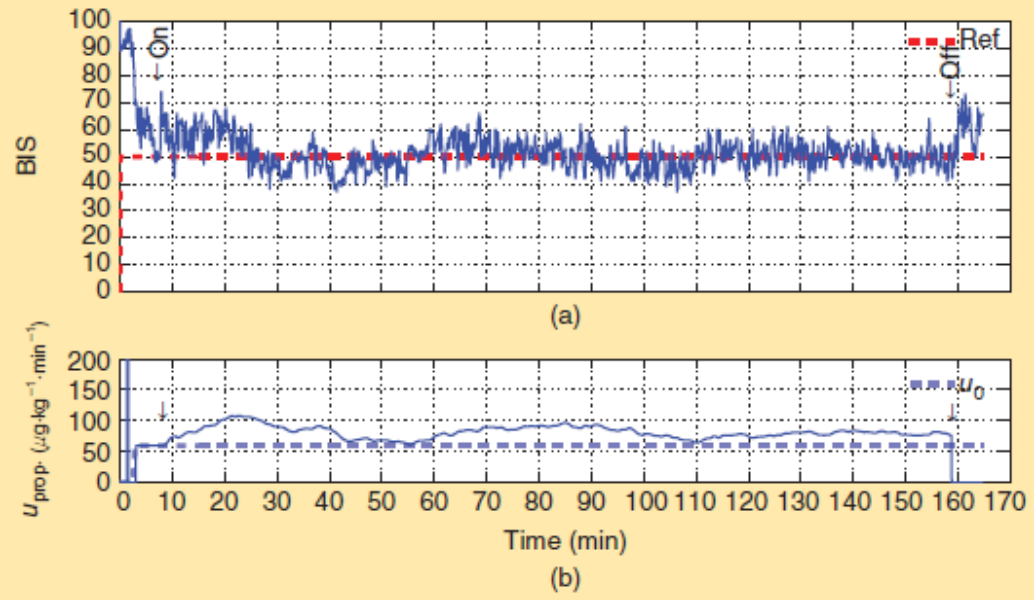
Control for anesthesia

J. M. Lemos et. al. (2014). Robust Control of Maintenance Phase Anesthesia. IEEE Control Systems, 34 (6): 24-38.

Available in Fénix

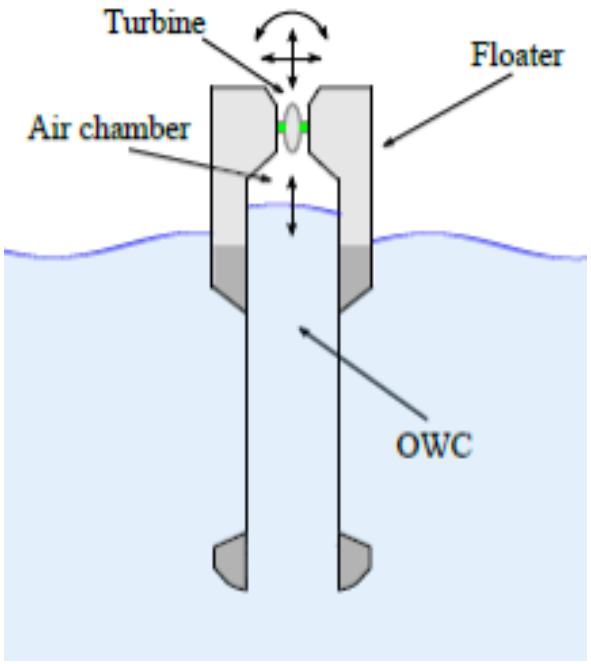

u_{prop}
Hypnotic Drug Infusion Rate
Hypnotic PK Model
C_e^{prop}
Hypnotic Drug Effect Concentration
Hill Equation
DoA
u_{remi}
Analgesic Drug Infusion Rate
Analgesic PK Model
C_e^{remi}
Analgesic Drug Effect Concentration


BIS
Time (min)


BIS
On
Off
Ref
(a)
u_{prop} ($\mu g \cdot kg^{-1} \cdot min^{-1}$)
u_0
Time (min)
(b)

Optimal control for sea wave energy

Source: Luis Gato, 2014



How to open and close the air valve to maximize the power transmitted from the wave train to the turbine?

J. Henriques, L. Gato, J. M. Lemos, R. Gomes, A. Falcão (2016). Peak-power control of a grid-integrated oscillating water column wave energy converter. *Energy*, 109: 378-390

Big challenges for control with major social impact and economic value

- Water management (drinking, agriculture, industrial use) and optimization
- Energy management and optimization; renewable energies
- Personalized healthcare (therapy as control design)
- Transportation
- Efficient and flexible manufacturing
- Efficient and reliable communications

Think these are old-fashion? Look at:

Systems & control for the future oh humanity, research agenda: Current and future roles, impact and grand challenges. F. Lamnabhi-Lagarrigue *et al.*, *Annual Reviews in Control*, 43: 1-64, 2017. Available in Fénix.

CEE provides essential tools to tackle engineering problems in these areas.

Put knowledge in action

This is a course that addresses theoretical basis.

However, many of them can be directly applied in a wide variety of fields with economical impact (Medicine, Nanotechnology, Agriculture, Aerospace, Mechatronics, Robotics, Energy, Telecommunications, Management…)

There is nothing more practical than a good theory (Boltzman)

Makers community (share knowledge to change the world):

- *http://makespace.org/*
- *https://en.wikipedia.org/wiki/Maker_culture*