[6.4200/16.405] **Robotics: Science and Systems**

Lecture 5-6: Embedded Control Systems

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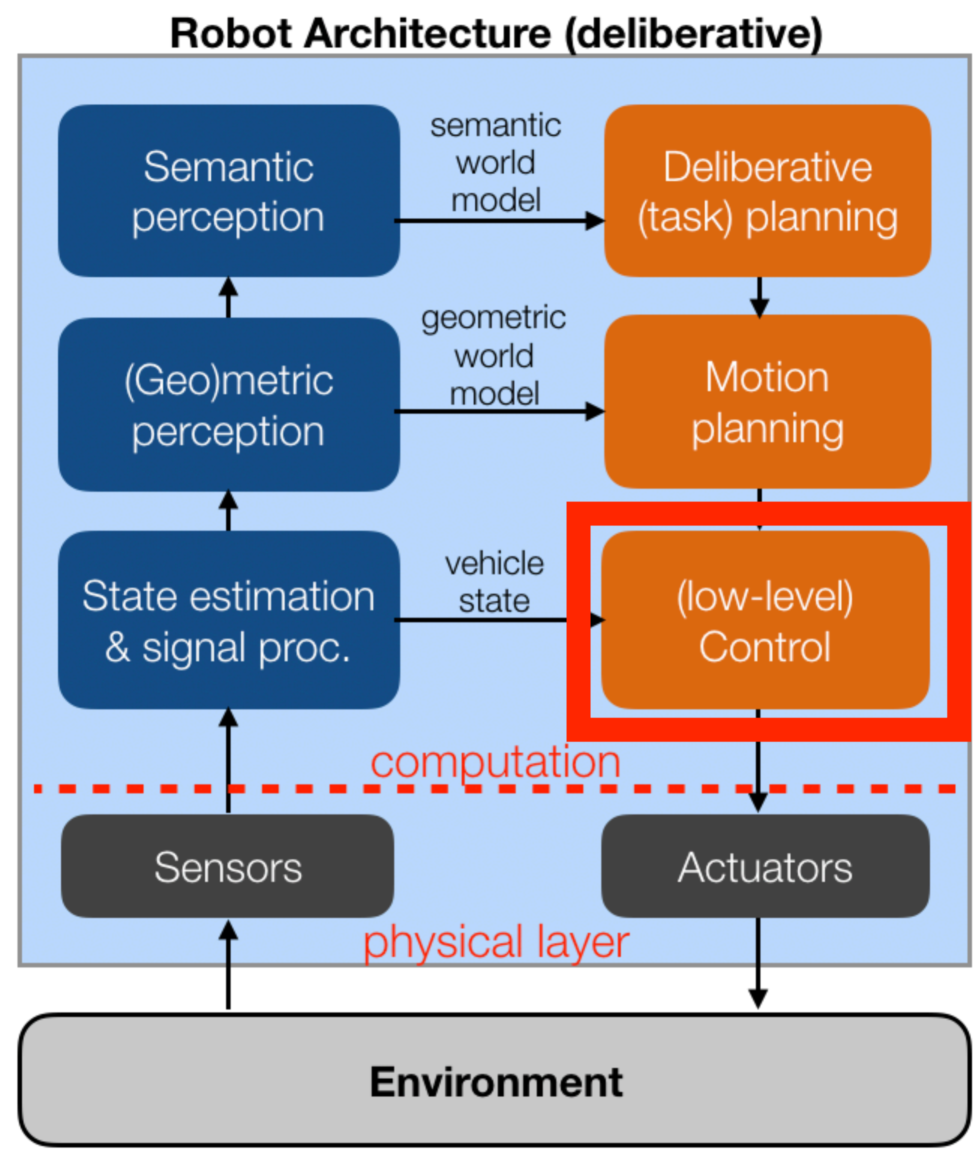
Slides by Sertac Karaman and Jon How

This week

Week	Dates	Lecture topic	Lab
1	Feb 6, Feb 8	Introduction, architectures, ROS	Lab1a-b: Linux, Git
2	Feb 13, 15	Geometry, more ROS	Lab1c: ROS
3	Feb 20, 22	Control and kinematics	Lab 2: wall following (simulation)
4	Feb 27, Mar 1	Sensing	Lab 3: wall following (racecar)
5	Mar 6, 8	Computer vision	Lab 4: visual servoing & lane following
6	Mar 13, 15	Perception I: world models & localization	Lab 5: localization & SLAM
7	Mar 20, 22	Perception II: mapping & SLAM	
	Mar 27-31	Spring break	
8	Apr 3, 5	Planning I: basic algorithms	Lab 6: planning & trajectory following
9	Apr 10, 12	Planning II: advanced algorithms	
10	Apr 17, 19	Machine Learning	Final Challenge: implementation
11	April 24, 26	Advanced topics and use cases	Final Challenge: implementation



Lecture Outline

- Introduction to control systems
  - a short history
  - role of negative feedback
- Basic control systems:
  - Feed-forward (FF) control
  - Bang-bang control
  - Proportional (P) control
  - Proportional-Derivative (PD) control
  - Proportional-Integral (PI) control
  - Proportional-Integral-Derivative (PID) control
  - —> Summary and Gain selection
- Application: steering control

The role of control

Many tasks in robotics are defined by *achievement* goals:

- "Go to the end of the maze"
- "Push that box over there"

} Planning

Other tasks in robotics are defined by *maintenance* goals:

- "Drive at 0.5m/s"
- "Keep a certain distance to the wall"
- "Keep the car within the lane"
- "Balance on one leg"

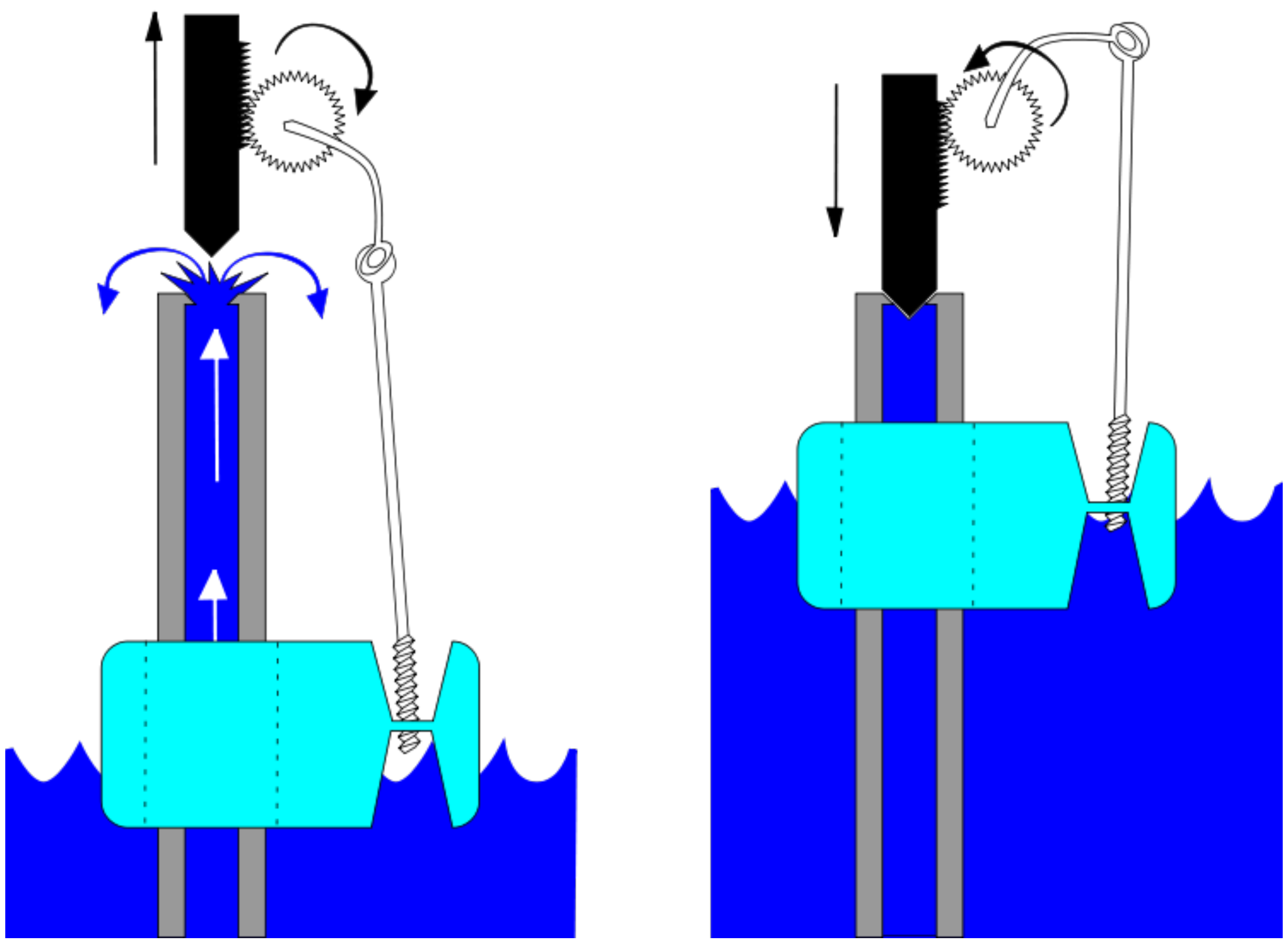
} Control

We will focus on control today; we will look at planning later!

What is the point?

- Consider any mechanism with adjustable DOFs (e.g., a valve, engine, car, robot, …)
- Control is *purposeful variation* of these DOFs to achieve some specified *maintenance state*.

*DOF = Degrees Of Freedom



Floating ball valve

The role of control

Control theory is generally used for low-level maintenance goals

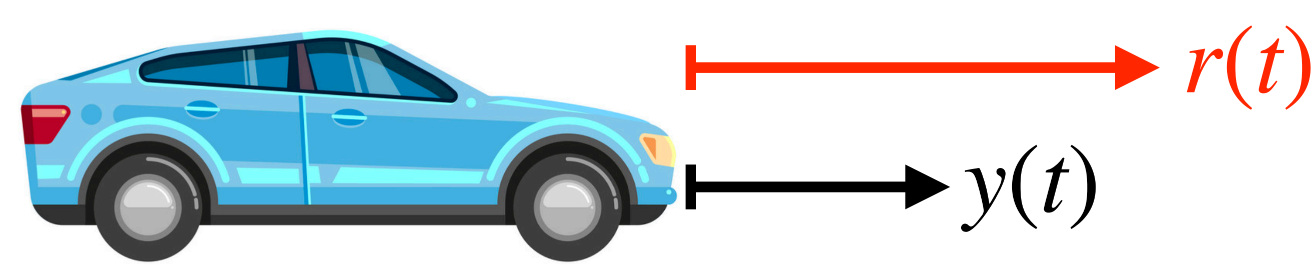
Input to the controller → Controller → Output of the controller

Error signal

(e.g., speed error, angle error)

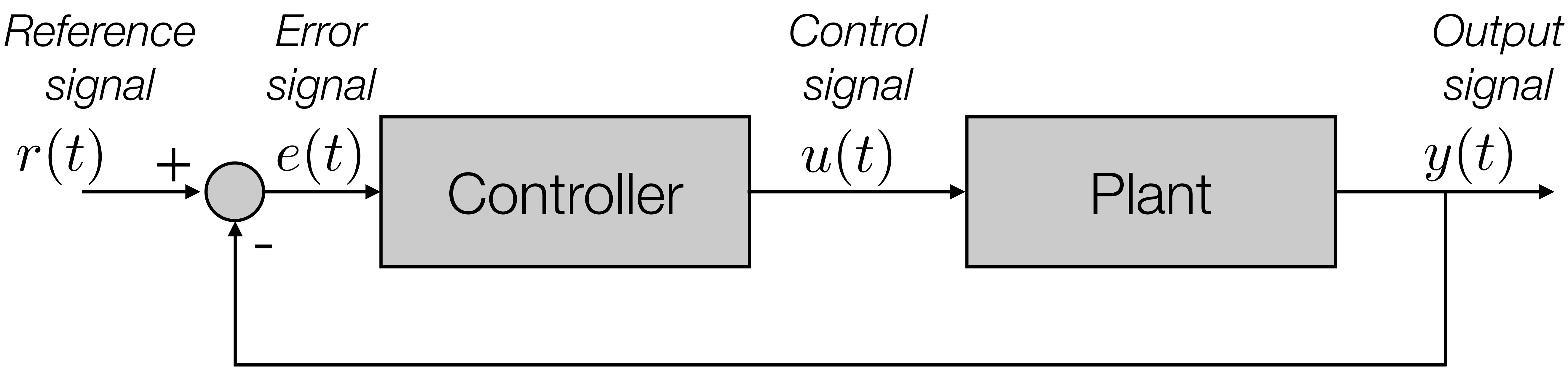
Actuator signal

(e.g., motor signal input)

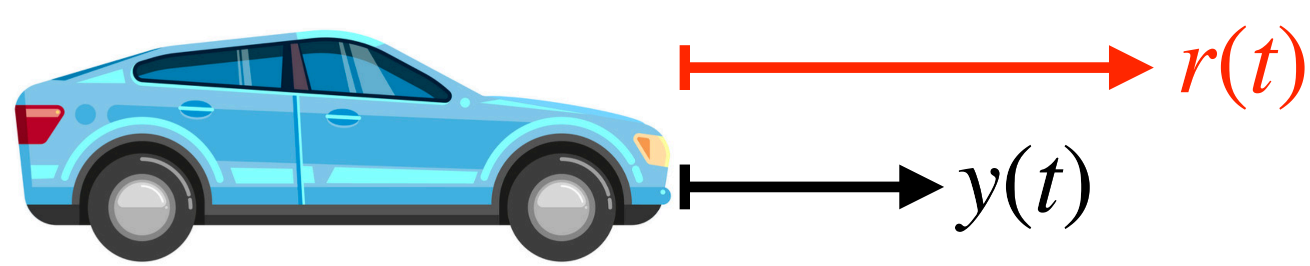


The role of control

The feedback control scheme

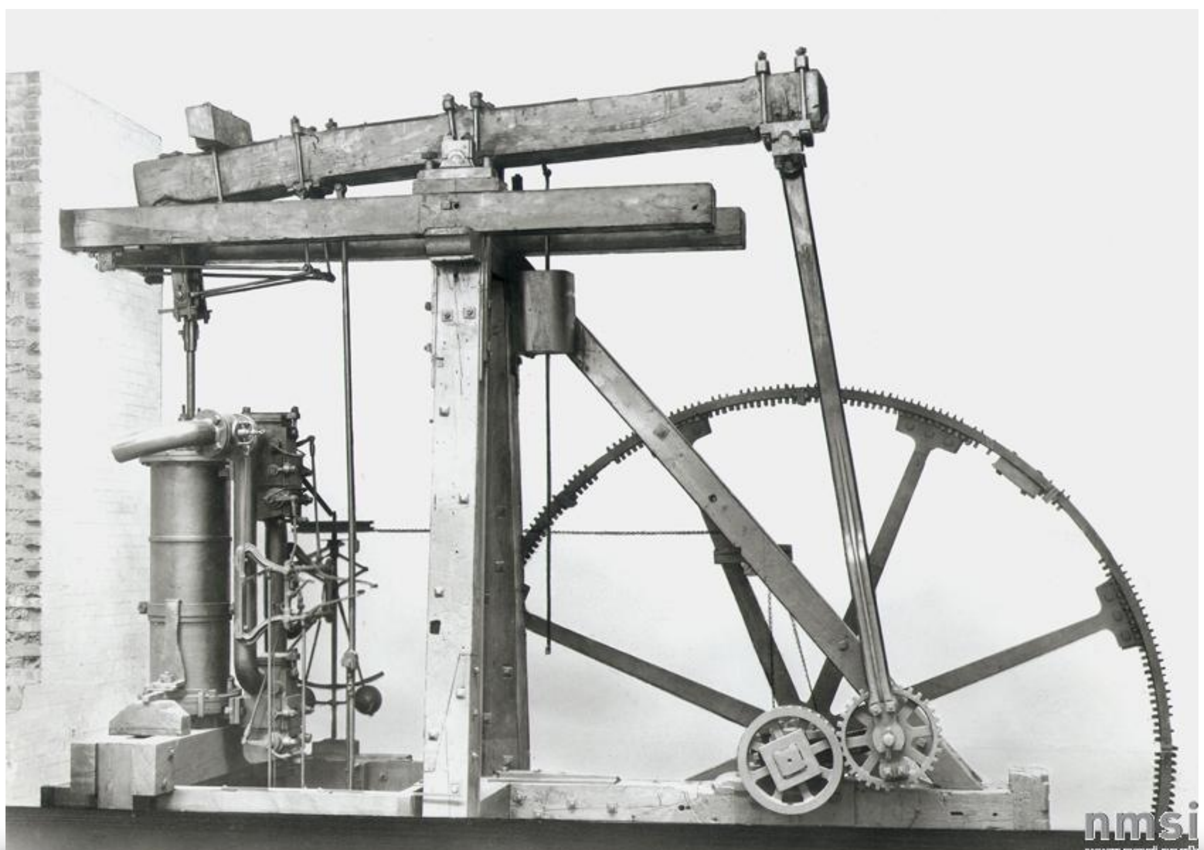


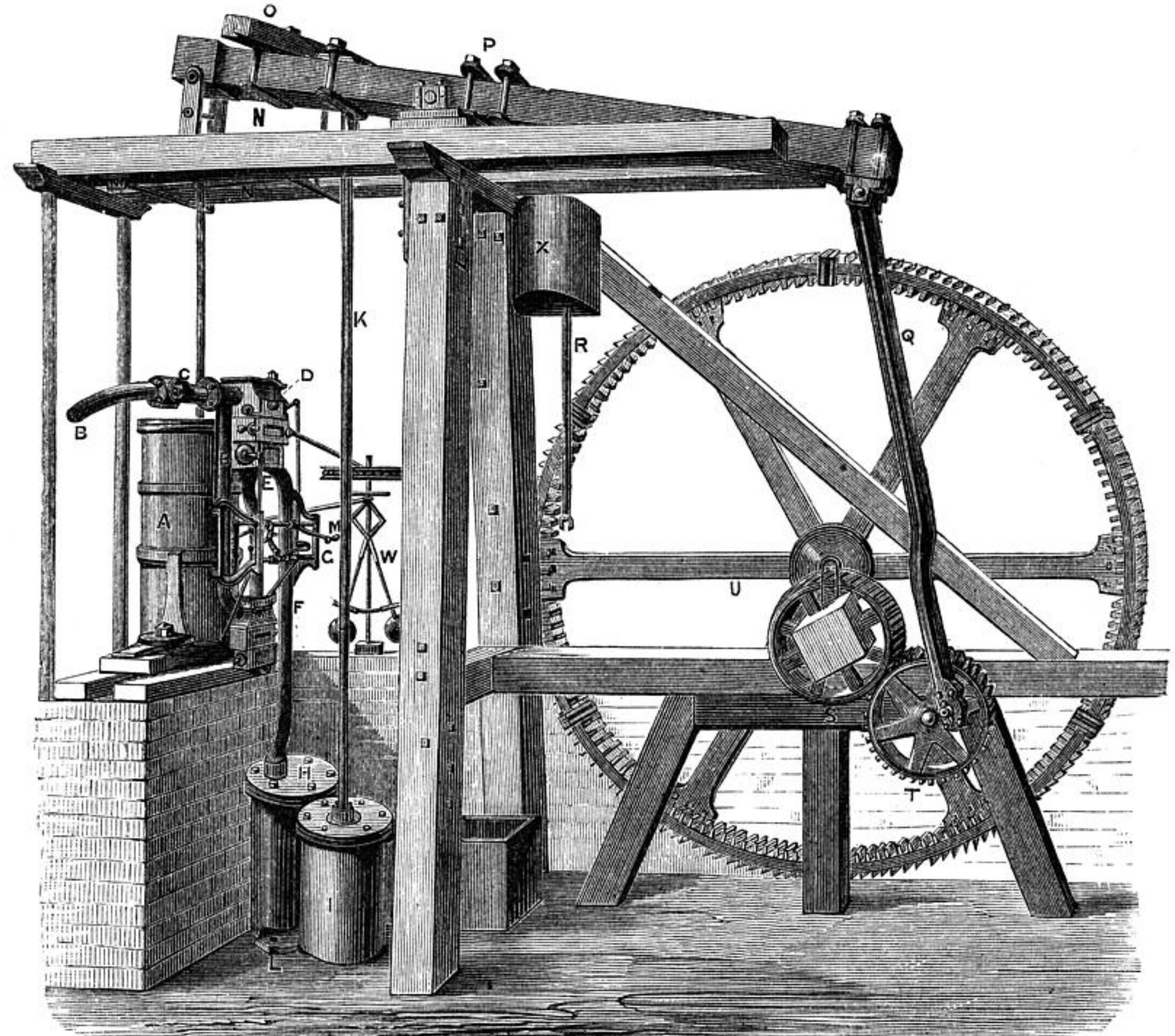
$$e(t) = r(t) - y(t)$$



Some history: control of mechanical systems

Control engineering during industrial revolution: rotary steam engine by Boulton and Watt (1788)





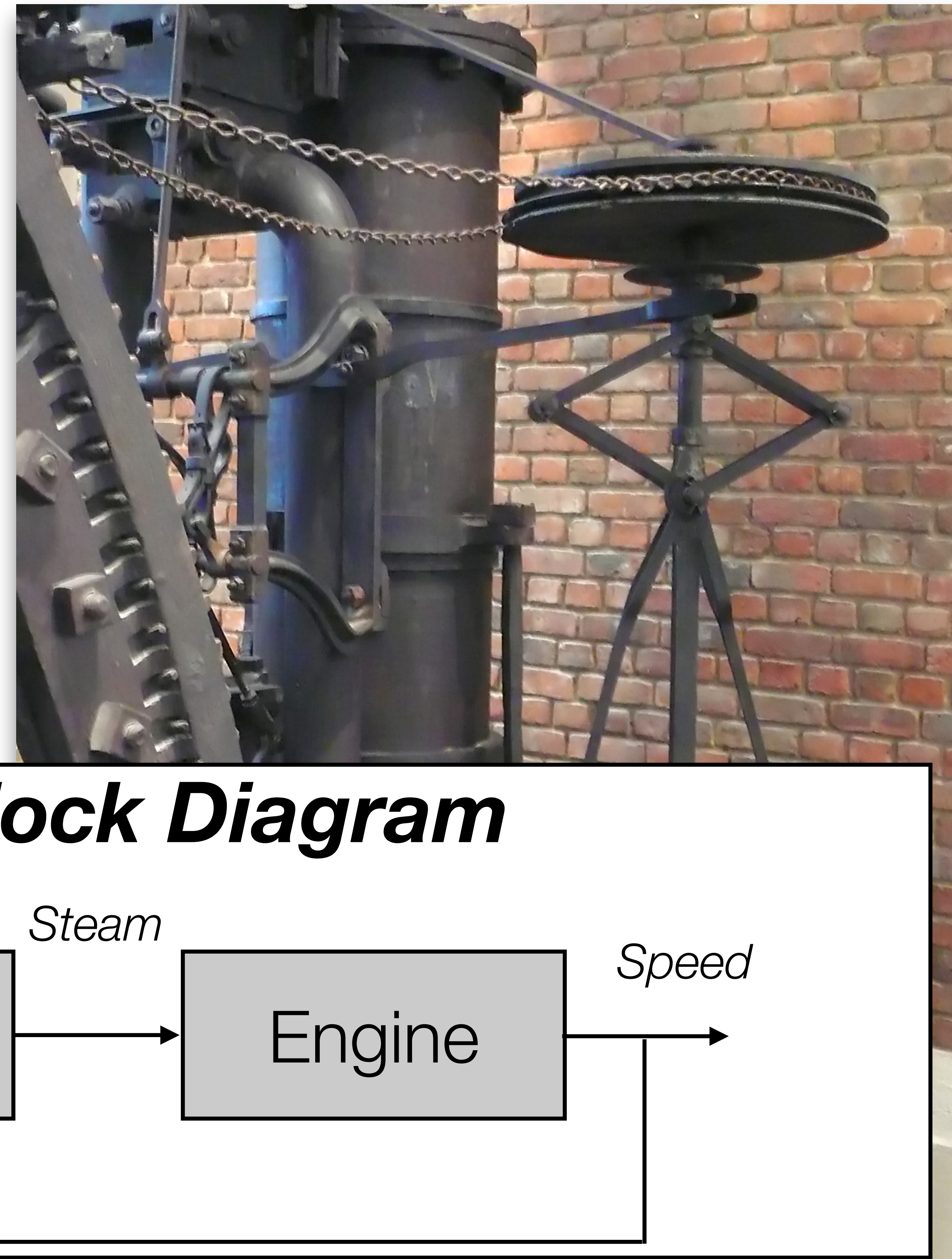
Watt's First Rotary Engine

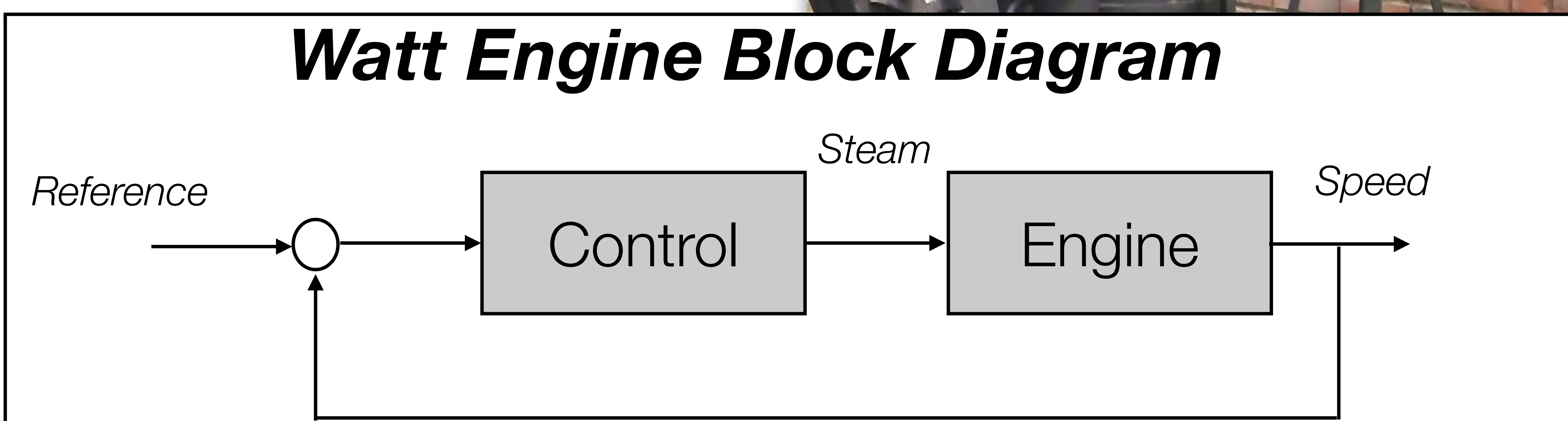
A. steam cylinder; B. steam pipe; C. throttle valve; D. steam valve; E. eduction valve; F. eduction pipe; G. valve gearing; H. condenser; I. air pump; K. air pump rod; L. foot valve; M. hand gear tappet rod; N. parallel motion; O. balance weight; P. rocking beam; Q. connecting rod; R. feed pump rod; S. sunwheel; T. planet wheel; U. fly wheel; W. governor; X. feed water cistern.

water pumping, locomotion of ships, trains, cars, etc.

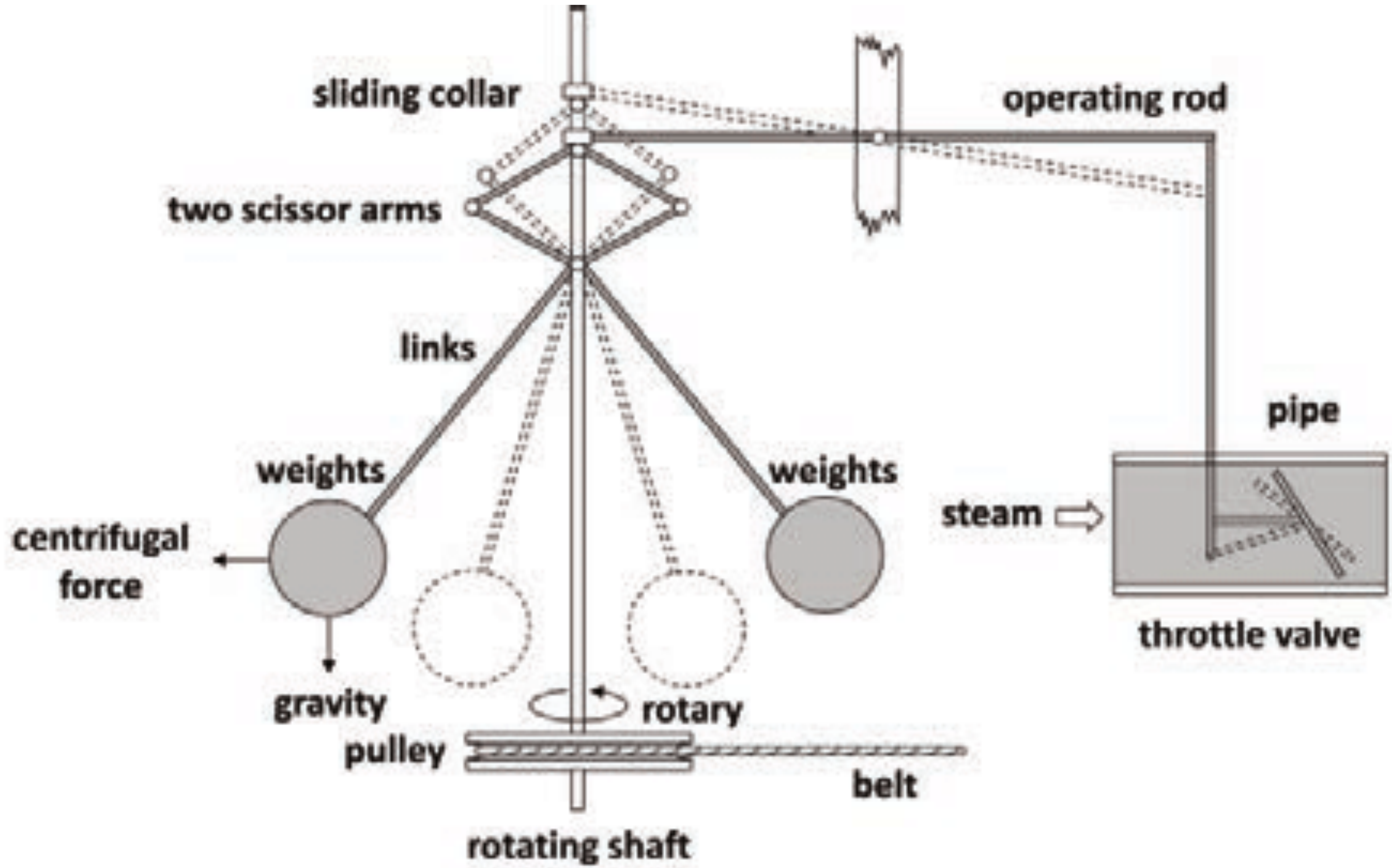
Some history: control of mechanical systems

Watt's engine: the centrifugal governor regulates the speed of the engine by varying the amount steam admitted into the cylinder.





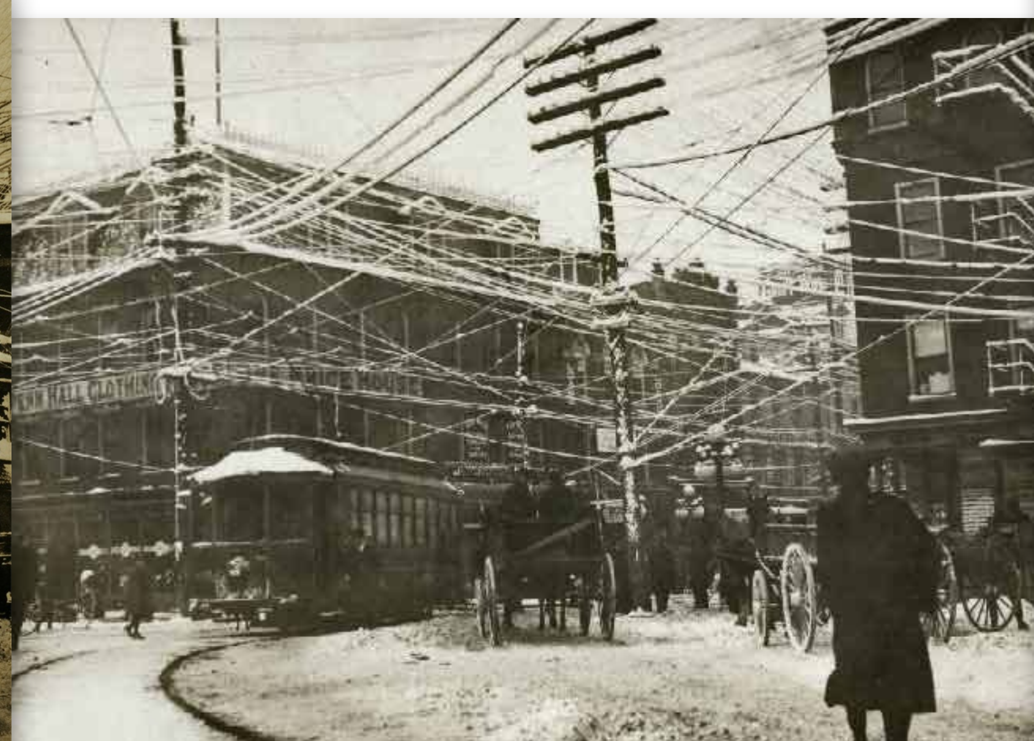
Some history: control of mechanical systems

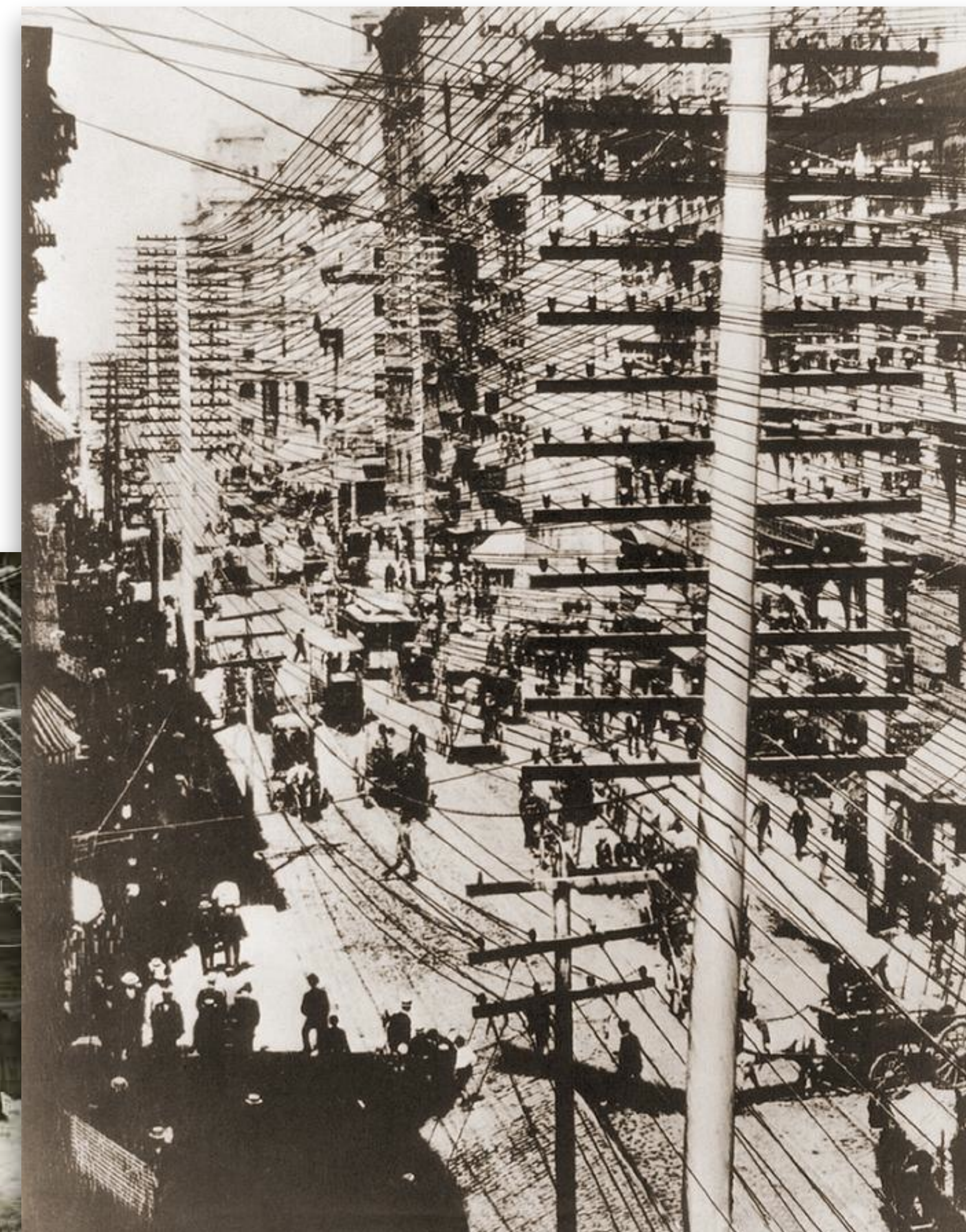


Some history: control of <u>electrical</u> systems

A century later: Telephone Wires in New York (1888)

- Telephone wires had taken over the major streets in New York
- Many were committed to engineering and improving the telephone network





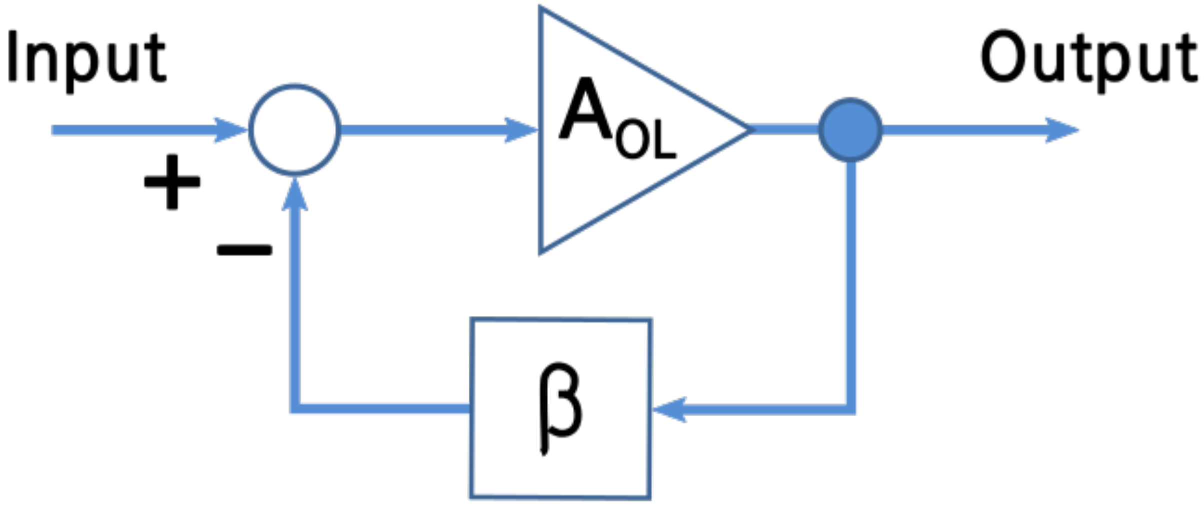
Some history: control of electrical systems

Bell Labs: how to improve quality of telephone communications?

- Big tech companies of the time: telephone companies, in particular the Bell Telephone Company, founded by Alexander Graham Bell
- In 1925, they formed and organized the Bell Laboratory

Bell Labs' work on amplifiers:

- Amplifiers are important for the transmission of telephone signals
- How can we design a *robust* amplifier, for instance for amplifying communication signals
- Solution: **negative feedback** amplifier



Negative Feedback control

- It was understood shortly that **negative feedback is universal**
- **Classical control theory** is influenced by the signals thinking (e.g., frequency plots, complex plane analysis)
- Later, **modern control theory** was developed later for designing complex control systems, such Apollo rockets

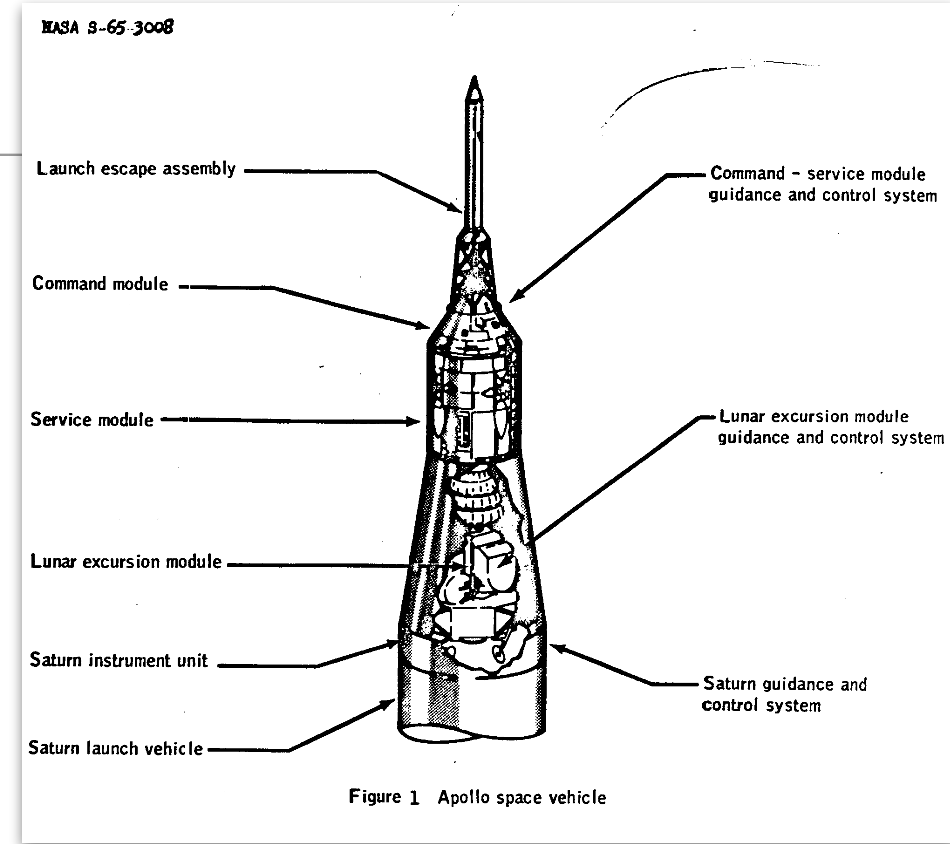


Figure 1 Apollo space vehicle

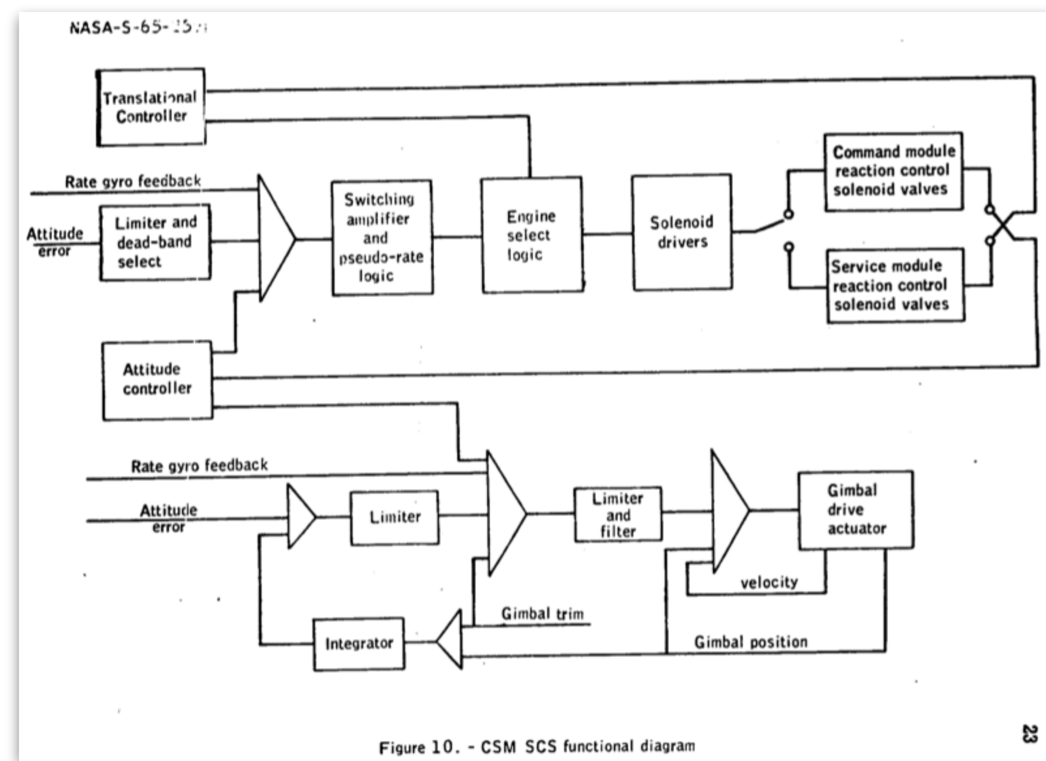
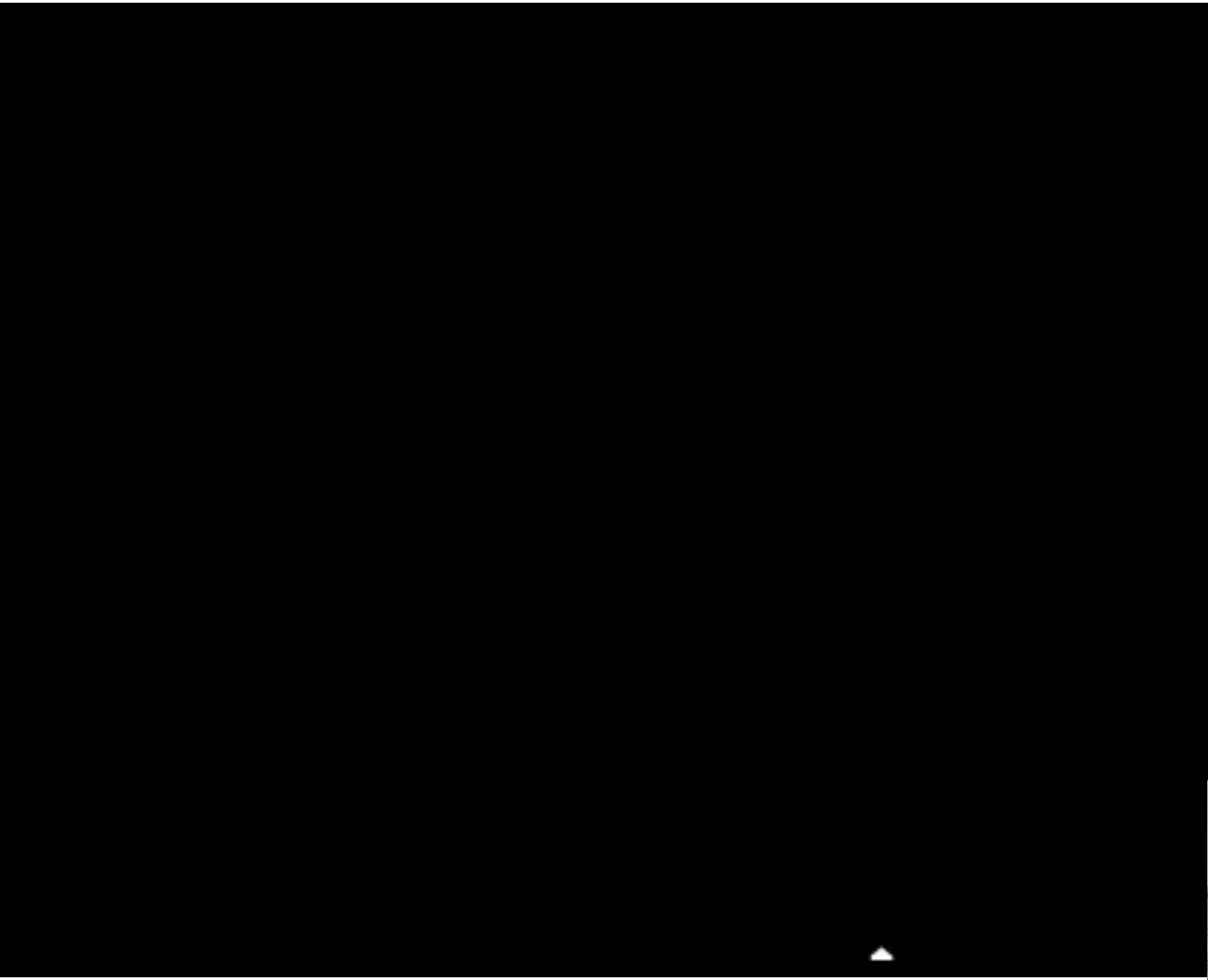


Figure 10. - CSM SCS functional diagram

Recent history: control for aerospace



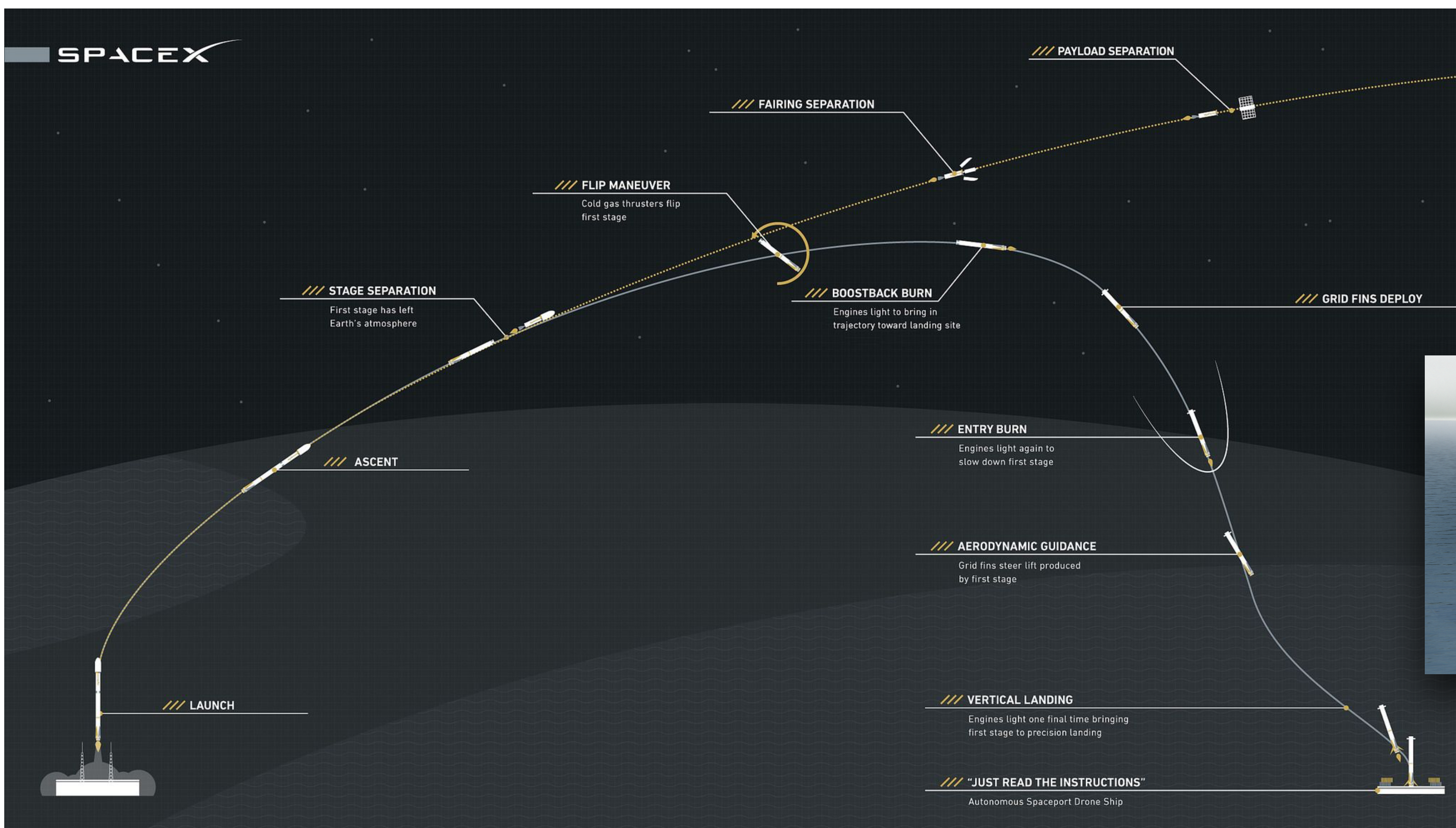
Curiosity Landing on Mars — August 2012

Ingenuity - 2021

Recent history: control for aerospace

Landing a Rocket

- rockets used once makes space flight extremely expensive
- reusable rockets would substantially reduce the cost of space flight
- SpaceX, Virgin Galactic, Blue Origin, … are all working on this technology



Recent history: control for <u>aerospace</u>

Grasshopper Rocket by SpaceX — April 2013

MIT Alumni lead the Guidance, Navigation and Control effort for the Grasshopper

Recent history: control for <u>aerospace</u>

Starship rocket by SpaceX — Feb 2021

SpaceX coolest video - rocket landing

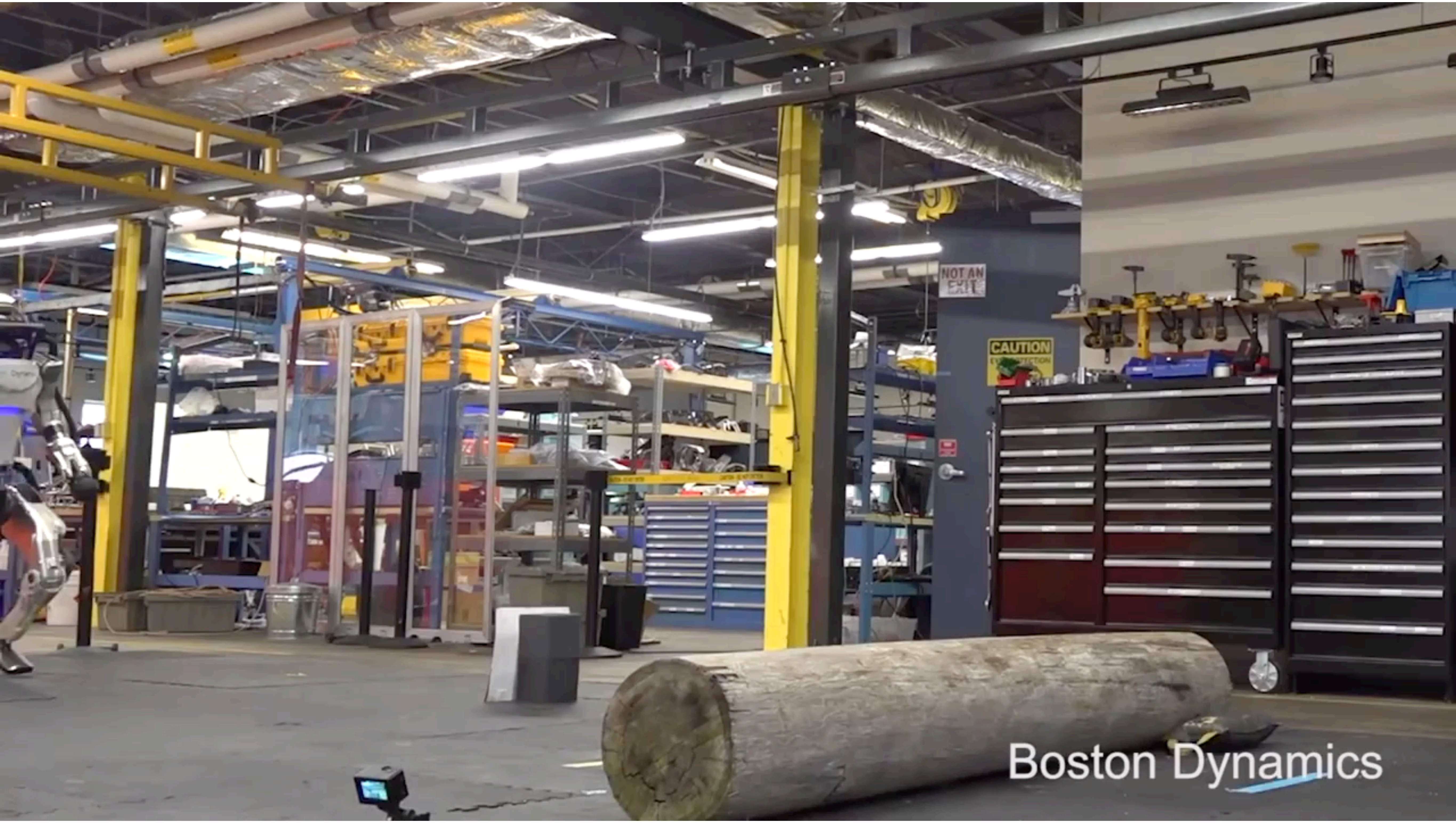
Recent history: control of <u>autonomous systems</u>

Balancing Pendulums with Quadrotors (ETH) — February 2013

Recent history: control of autonomous systems

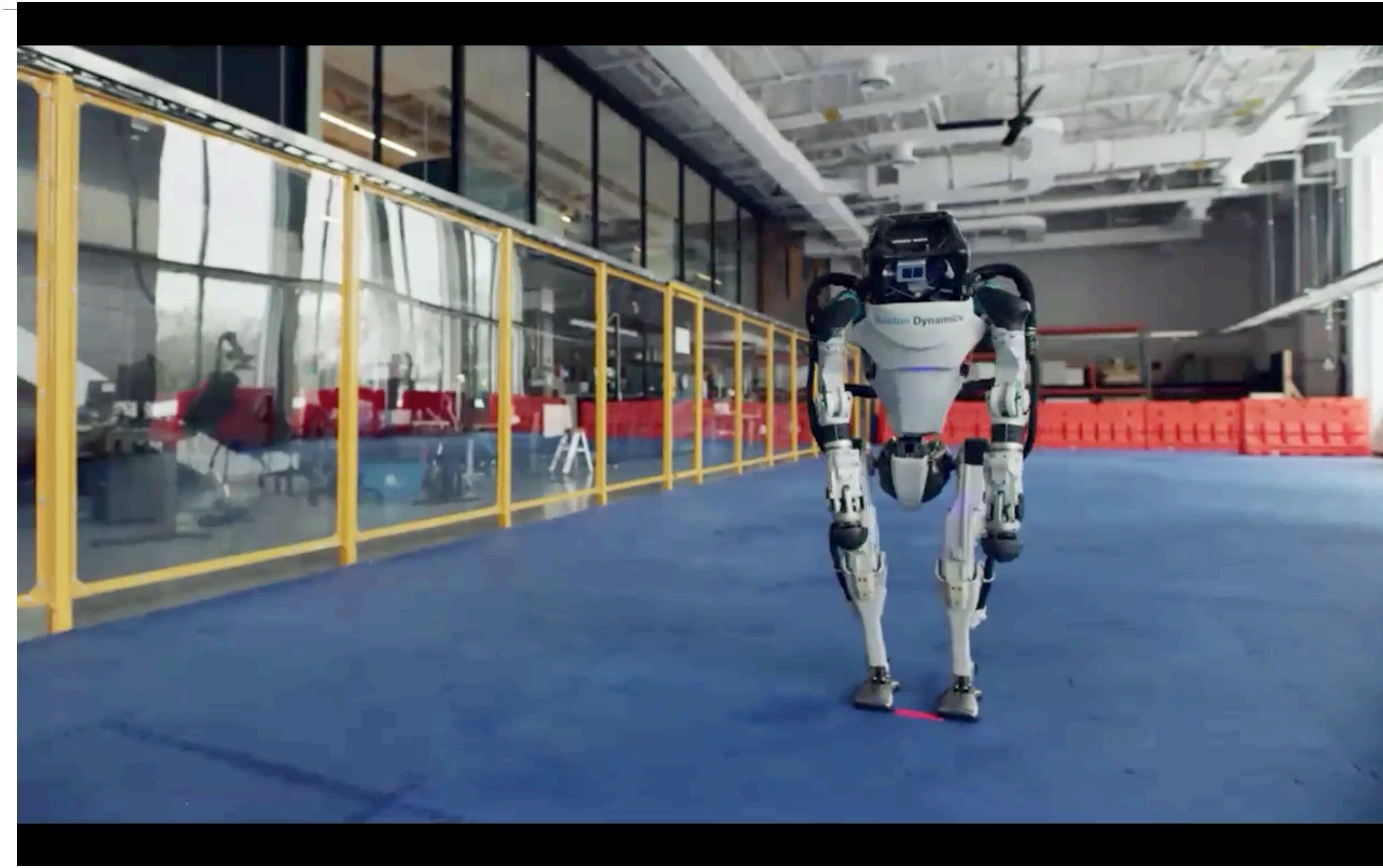
Robot Balances itself (Boston Dynamics - then Google) — 2014

Recent history: control of autonomous systems



Robot Balances runs around (Boston Dynamics - then Softbank) — 2018

Recent history: control of autonomous systems



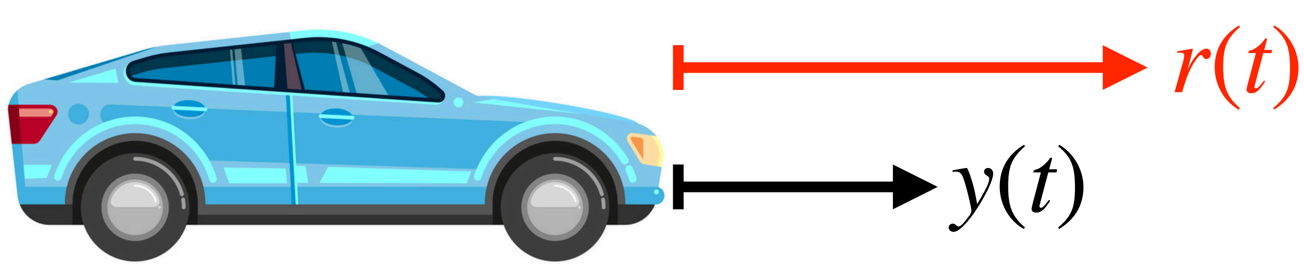
Robots dance (Boston Dynamics - now Hyundai Motor Group) — 2020

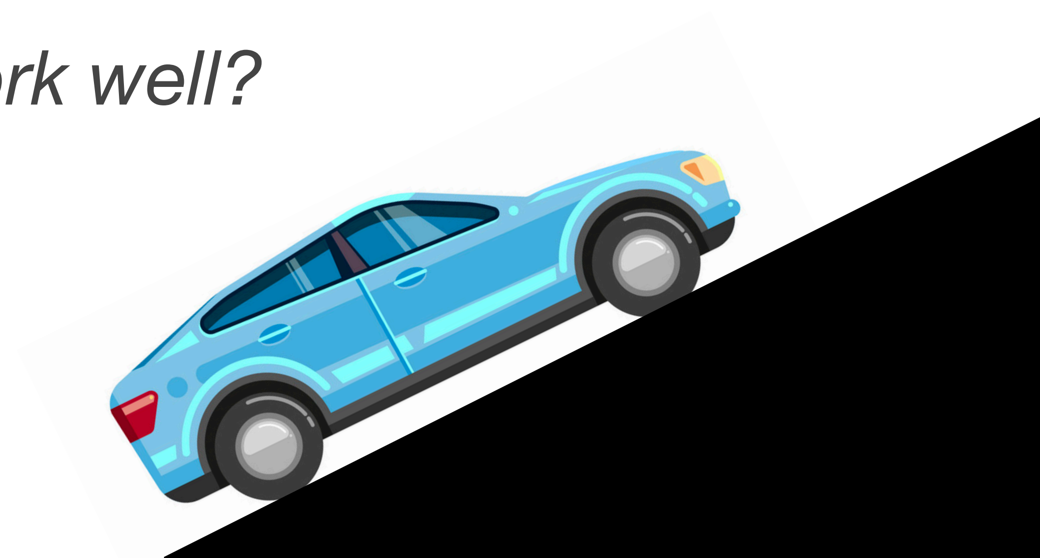
https://youtu.be/fn3KWM1kuAw

Feed-Forward (FF) Control

- Pass control signal from external environment directly to the actuator
- The control signal is typically multiplied by a gain

- *What are the units of the control signal?*
- *Where does the gain value K come from?*
- *Under what conditions does FF control work well?*





Feedback Control: Driving to a point

Feedback Control: Driving to a point

$$\min_{x,u} \quad \frac{1}{2}||x - x_g||^2$$

$$\text{s.t.} \quad \boxed{x = x_0 + u}$$

Forward Dynamics Constraint

Feedback Control: Driving to a point

$$\min_{x,u} \quad \frac{1}{2}||x - x_g||^2$$

$$\text{s.t.} \quad \boxed{x = x_0 + u}$$

What are the practical drawbacks of this solution?

Forward Dynamics Constraint

FF Solution: $u^* = x_g - x_0$

x_0 x_g

Feedback Control: Driving to a point

$$\min_{x,u} \quad \frac{1}{2}||x - x_g||^2 + \frac{1}{2}u^2$$

$$\text{s.t.} \quad x = x_0 + u$$

FB Solution: $u_t^* = \frac{1}{2}\left(x_g - x_t\right)$

Feedback Control

- Feedback control systems are more robust to the discrepancies in our understanding of the plant, such as un-modeled dynamics and parameter uncertainties.