Closed-loop control

aka feedback-based control

Definitions and motivations; bang-bang control; PID control; PID tuning

Reference: https://en.wikipedia.org/wiki/PID_controller Some slides credit: Prof. Edwin Olson, University of Michigan

Robot goals

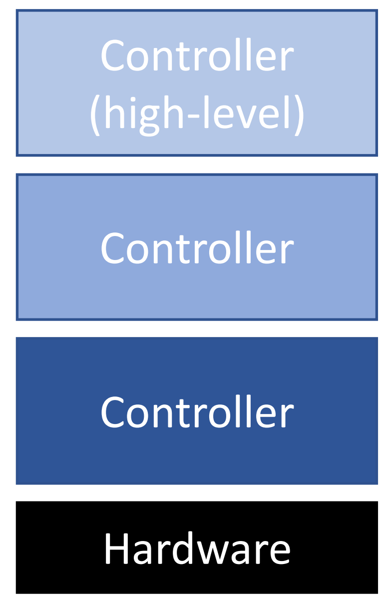
- **High-level** (*achievement goals*), i.e.
  - “your purpose is to pass the butter”
  - “remove all weeds from this field”
  - “exterminate all humanity”
- **Low-level** (*maintainance goals*): act in such a way that a variable reaches and maintains a given value
  - **Open-loop** control

    “know your system”: If I command the motors to full power for three seconds, then I know I’ll go forward one meter. I never observe the result to adjust my action to the actual state.
  - **Closed-loop** control

    Use a feedback to adjust control while the action takes place

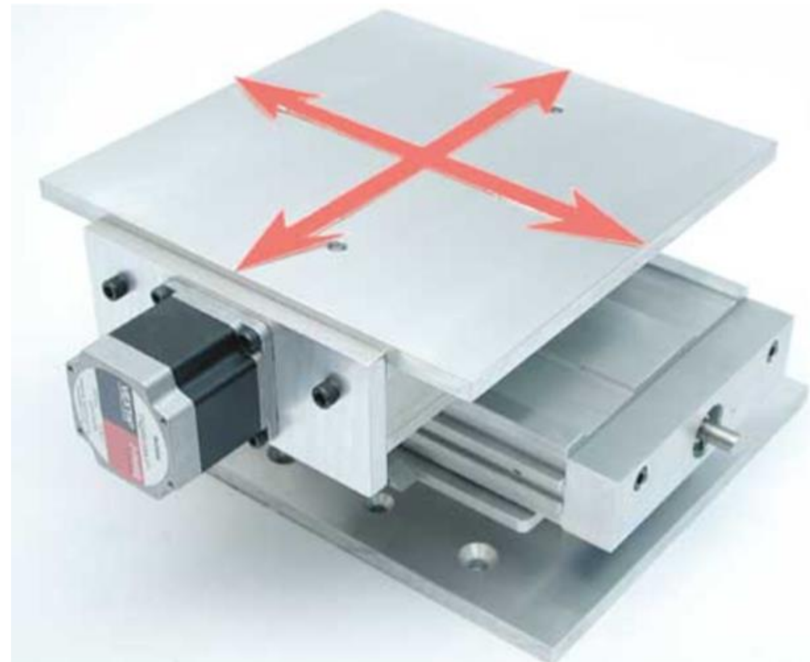
Real-world systems implement a complex hierarchy of controllers

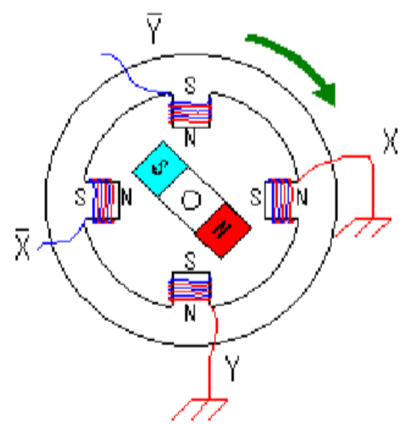
https://youtu.be/X7HmltUWXgs



An example of an open-loop system

Electric stepper motors are built in such a way to not require any feedback to precisely control them

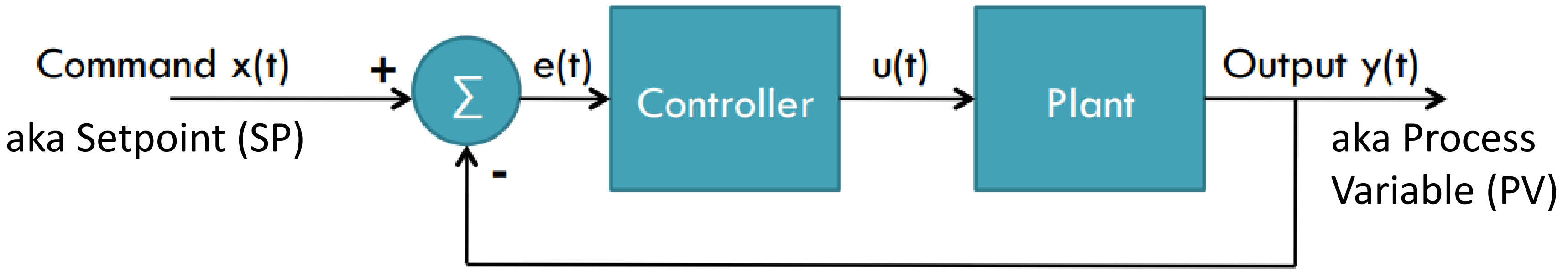




X	$\bar{X}$	Y	$\bar{Y}$
0	1	0	1
1	0	0	1
1	0	1	0
0	1	1	0

Credit: electricsteppermotors.com

Closed-loop control



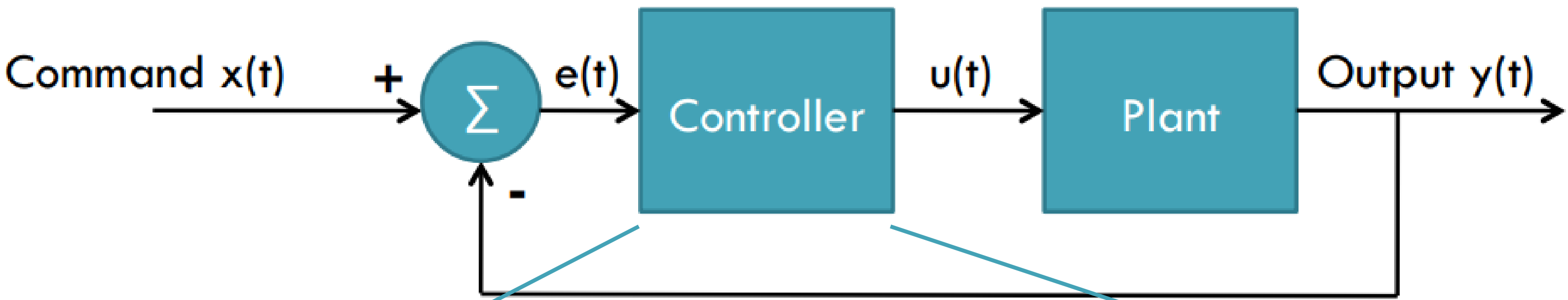
Given a desired output x(t)

- Observe the actual output y(t)
- Compare y(t) with x(t) to obtain error e(t)
- Decide input u(t) as a function of e(t)

Note: we have a rough idea about how u(t) affects e(t):

- If u(t) is large/positive, y(t) will increase, e(t) will decrease
- If u(t) is small/negative, y(t) will decrease, e(t) will increase

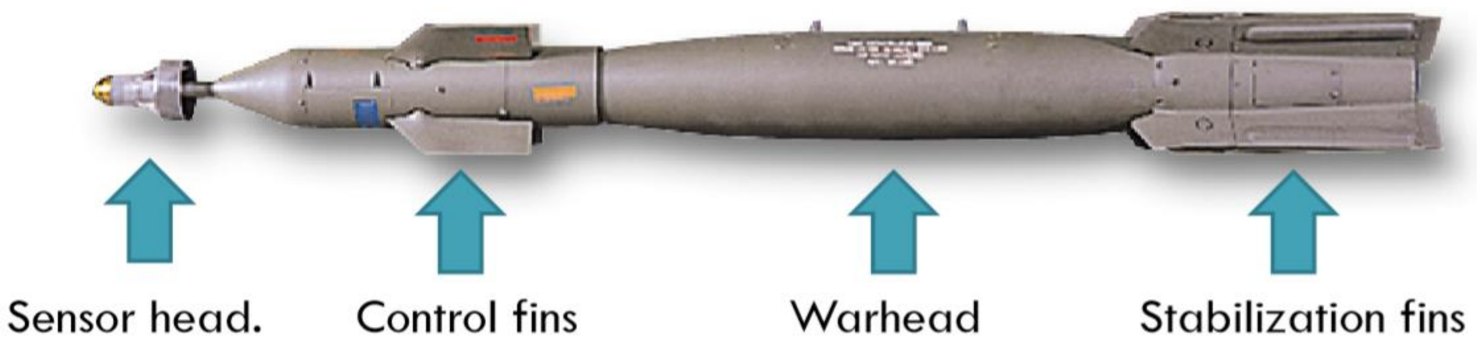
Bang-bang controller

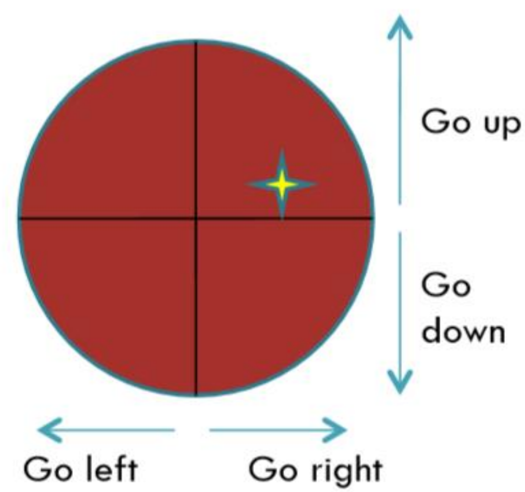



```
if e(t) > 0
      u(t) = maximum_allowed_value
else
      u(t) = minimum_allowed_value
```

An application of bang-bang control

GBU-12 Paveway II Laser Guided Bomb





Sensor head detects laser spot in one of four quadrants

An application of bang-bang control

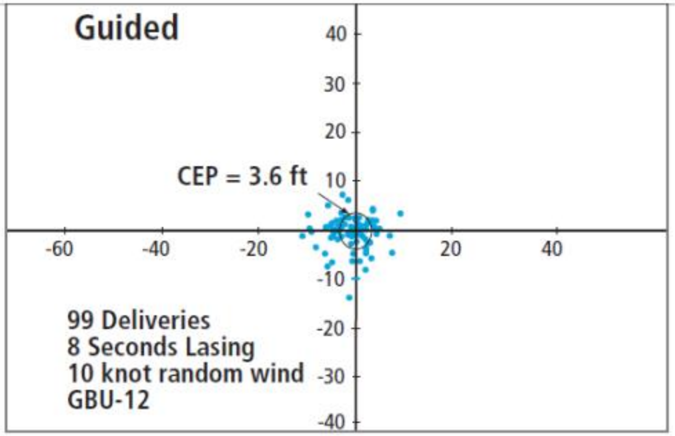
Advantages:

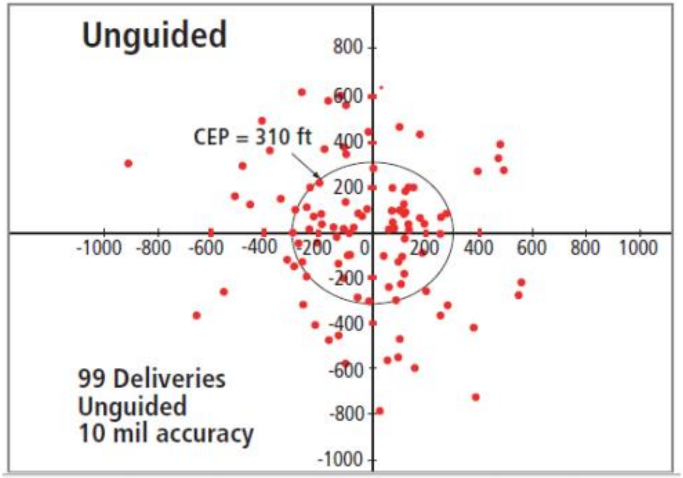
- Super simple actuators
- Better than open loop!
- Simple, cheap, predictable
- No calibration

Disadvantages:

- less precise / slower than other controllers

Wikipedia: Paveway II laser-guided bombs use what is known as "bang bang" guidance. This means the bomb's fins deflect fully, rather than proportionally when it is attempting to guide to the laser spot. For example, if it sees the laser spot and determines that it should make a change it deflects its fins until it has over-corrected and then it deflects back the opposite direction, creating a sinusoidal type of flight path. This type of guidance may be less efficient at times, however is more cost effective and allows the use of simpler electronics in the guidance system.





Proportional Control

$$u(t) = K_p e(t)$$

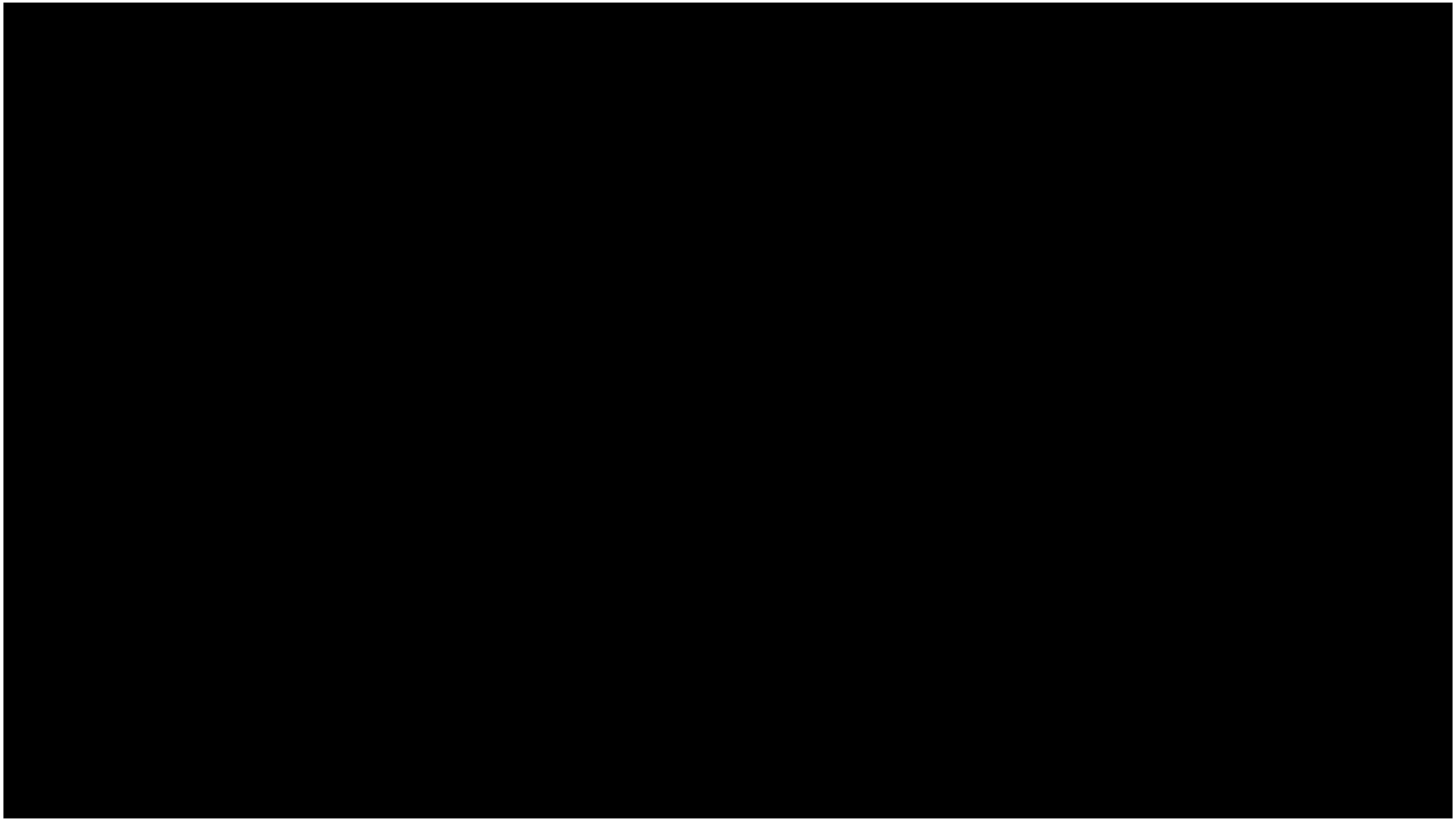
Proportional gain

To act quickly you want a large gain

We want to get rid of steady-state error: if we are close to desired output, proportional output will be small. This makes it hard to drive steady-state error to zero

With really large gains we are back to bang-bang control.

Bang bang vs proportional



https://www.youtube.com/watch?v=t3R9cPq1aYk

Derivative control

$$u(t) = K_d \frac{d}{dt} e(t)$$

Derivative gain

The system under control often has some sort of inertia.

The action I take should depend on the rate of change of the error. If it is decreasing fast, I should act differently than if is stationary.

In practice, this helps reducing oscillations

PD Control = Proportional + Derivative

- P seeks error = 0
- D seeks derivative of error = 0

- D term helps dampen oscillation
  - Allows for larger P → Faster response

Integral control

- Suppose we're in steady state, close to desired value.
  - D term is zero
  - P term is nearly zero
- P term may not be strong enough to force error to zero!
- If we have error for a long period of time, it argues for additional correction.
  - Integrate error over time, add to command signal.
  - Force average error to zero (in steady state)

PID Controller

$$u(t) = K_p e(t) + K_d \frac{d}{dt} e(t) + K_i \int e(t)$$

- Use the simplest controller that achieves the expected performance
- Often P or PD are sufficient. Sometimes PI.
- Integral term effect is difficult to predict and hard to tune. Often, one "clamps" the integrator to limit its effect

PID tuning approaches

PID Tuning = determine a value for K_p, K_i, K_d that yields satisfactory performance

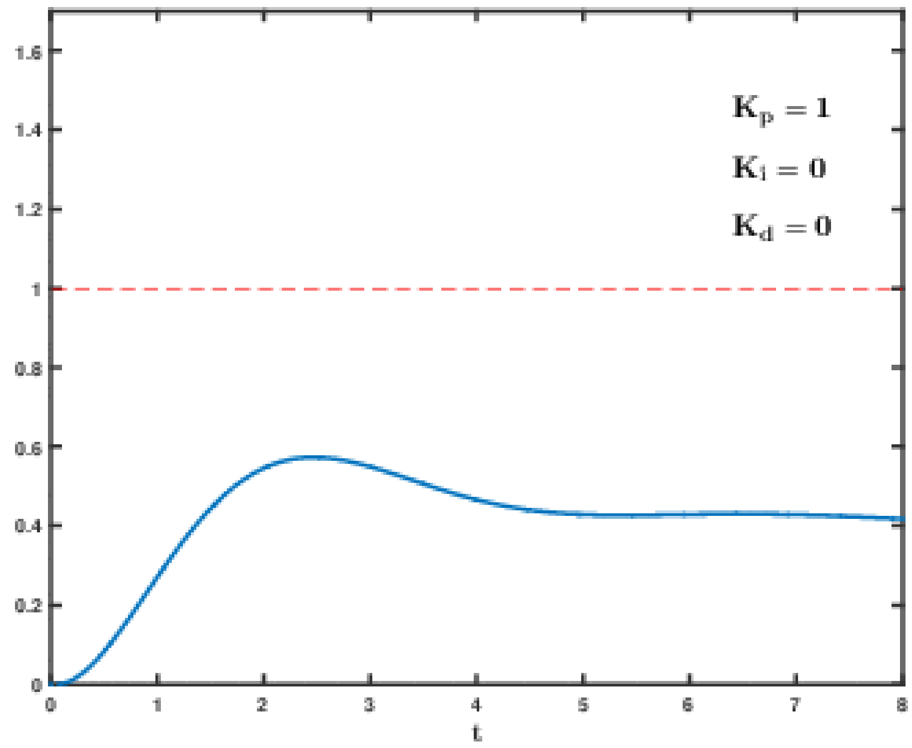
- Analysis
  - Carefully model system in terms of underlying physics and PID controller gains.
  - Compute values of PID controller so that system is stable and performs well
- Empirical experimentation
  - Hard to make models accurate enough: many parameters
  - Often, easy to tune by hand using the actual system

PID tuning for dummies

1. Increase P term until performance is adequate or oscillation begins
2. Increase D term to dampen oscillation
3. Go to 1 until no improvements possible.
4. If needed, increase I term to eliminate steady-state error.

PID tuning for dummies (alternative approach with nifty GIF)

1. Increase P term until performance is adequate or oscillation begins
2. Increase I term to eliminate steady-state error
3. Increase D term to minimize oscillations



Animation: Wikimedia user Physicsch [CC0]
https://upload.wikimedia.org/wikipedia/commons/3/33/PID_Compensation_Animated.gif

Effects of P, I, D tuning: summary

TABLE 1 Effects of independent P, I, and D tuning on closed-loop response. For example, while K_I and K_D are fixed, increasing K_P alone can decrease rise time, increase overshoot, slightly increase settling time, decrease the steady-state error, and decrease stability margins.

	Rise Time	Overshoot	Settling Time	Steady-State Error	Stability
Increasing K_P	Decrease	Increase	Small Increase	Decrease	Degrade
Increasing K_I	Small Decrease	Increase	Increase	Large Decrease	Degrade
Increasing K_D	Small Decrease	Decrease	Decrease	Minor Change	Improve

PID tuning intuition

https://www.youtube.com/watch?v=K-F_T59ZDPw

A well tuned PID

https://www.youtube.com/watch?v=qKy98Cbcltw

The Ziegler–Nichols method (1941), a heuristic for PID tuning

1. Set the I and D gains to zero
2. Increase K_p from zero until it reaches the ultimate gain K_u at which the output of the control loop has stable and consistent oscillations
3. K_u and the oscillation period T_u are used to set the P, I, and D gains depending on the type of controller, as per the table below

Control Type	K_p	K_i	K_d
P	$0.5K_u$	–	–
PI	$0.45K_u$	$0.54K_u/T_u$	–
PD	$0.8K_u$	–	$K_uT_u/10$
classic PID	$0.6K_u$	$1.2K_u/T_u$	$3K_uT_u/40$
some overshoot	$K_u/3$	$0.666K_u/T_u$	$K_uT_u/10$
no overshoot	$K_u/5$	$2/5K_u/T_u$	$K_uT_u/15$

Optimum Settings for Automatic Controllers

By J.G. ZIEGLER[1] and N. B. NICHOLS[2] • ROCHESTER, N. Y.

In this paper, the three principle control effects found in present controllers are examined and practical names and units of measurement are proposed for each effect. Corresponding units are proposed for a classification of industrial processes in terms of the two principal characteristics affecting their controllability. Formulas are given which enable the controller settings to be determined from the experimental or calculated values of the lag and unit reaction rate of the process to be controlled. These units form the basis of a quick method for adjusting a controller on the job. The effect of varying each controller setting is shown in a series of chart records. It is believed that the conceptions of control presented in this paper will be of assistance in the adjustment of existing controller applications and in the design of new installations.

A PURELY mathematical approach to the study of automatic control is certainly the most desirable course from a standpoint of accuracy and brevity. Unfortunately, however, the mathematics of control involves such a bewildering assortment of exponential and trigonometric functions that the average engineer cannot afford the time necessary to plow through them to a solution of his current problem.

It is the purpose of this paper to examine the action of the three principal control effects found in present-day instruments, assign practical values to each effect, see what adjustment of each does to the final control, and give a method for arriving quickly at the optimum settings of each control effect. The paper will thus first endeavor to answer the question: "How can the proper controller adjustments be quickly determined on any control application?" After that a new method will be presented which makes possible a reasonably accurate answer, to the question: "How can the setting of a controller be determined before it is installed on an existing application?"

Except for a single illustrative example, no attempt will be made to present laboratory and field data, to develop mathematical relations, or to make acknowledgment of material from published literature. A paper covering the mathematical derivations would be quite lengthy as would also a paper covering laboratory and field-test results. Work on these phases of the subject is still under way, and it is expected that the results will be published at a later time when convenient. It is believed advisable to publish the present paper without delay in order to make the information available for use by the many persons interested in the application of automatic-control instruments. To these persons the present subject matter is of much greater interest than the other phrases of the study which are being omitted.

To simplify terminology we will take the most common type of control circuit in which a controller interprets the movement of its recording pen into a need for corrective action, and, by varying its output air pressure, repositions a diaphragm-operated valve. The controller may be measuring temperature, pressure, level, or any other variable, but we will completely divorce the measurement portion of the control circuit and speak only of the pen movement in inches; 1 in. of pen movement might represent 1 or 1000 deg F, or a flow of 1 or 1000 gpm. The actual graduation will be of no moment in a study of control.

Our controller will translate pen behavior into behavior of a valve; the relation between the two behavior patterns is determined by the setting of each control effect. The term valve covers any similar device, i.e., a damper or rheostat which must be operated by the controller in order to maintain correct process conditions.

Proportional Response

In spite of the multitude of air, liquid, and electrically operated controllers on the market, all are similar in that they incorporate one, two, or, at most three quite simple control effects. These three can be called "proportional," "automatic reset," and "pre-act."

Proportional Response. By far the most common effect is "proportional response," found in practically all controllers. It gives a valve movement proportional to the pen movement, that is, a 2-degree pen movement gives twice as much valve movement as a 1-degree pen movement. Simple spring-loaded pressure-reducing valves are really proportional-response controllers in that, over a short range of pressure, the valve is moved proportionally from one extreme to the other.

Sensitivity. The measure of proportional response is called "sensitivity" or "throttling range;" the former being valve movement per pen movement, the latter its reciprocal or the pen movement necessary to give full valve movement. Either sensitivity or throttling range describes the magnitude of proportional response, though in this paper each response will be measured in units which increase as the relative valve action per pen action increases. In the case of proportional response, the unit will accordingly be called "sensitivity."

Proportional-response sensitivity in some controllers is not adjustable; in most, however, it may be adjusted either continuously or in steps over a considerable range. If we define sensitivity as the output pressure change per inch of pen travel, it is apparent that the limits would be from zero (manual control) to infinitely high (on-off control). Perhaps the widest range of adjustment is found in one controller with sensitivity continuously variable from 1000 to 1 psi per in. A sensitivity of 1000 gives 1 psi output change for each 0.001 in. of pen travel.

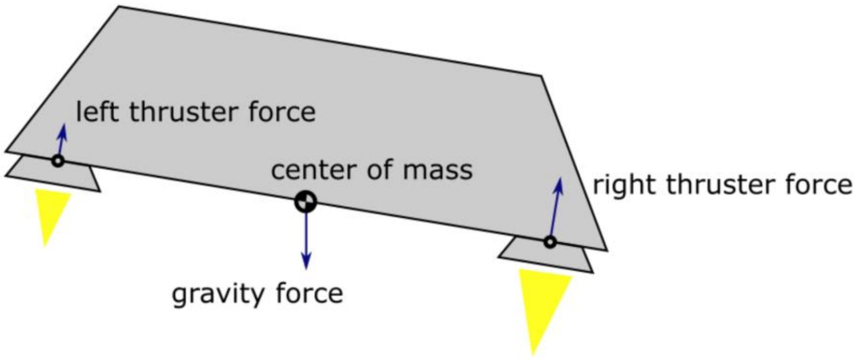
Sensitivity adjustment is necessary if optimum control stability is to be attained. It is common knowledge that control with infinitely high proportional response is always unstable, oscillating continuously. True, on certain applications the oscillation may be of such small magnitude that it is not objectionable and, if the surges in supply are not serious in their effect on other portions of the process the control obtained may be entirely acceptable.

Industry generally demands control of the "throttling" type rather than "on-off" since, a proportional-response controller, set in any sensitivity below some maximum, will produce a damped oscillation and eventually straight-line control.

Amplitude Ratio. Sensitivity adjustment affects primarily the stability of control. On any application there is a definite and

[1] Sales Engineering Department, Taylor Instrument Companies.
[2] Engineering Research Department, Taylor Instrument Companies

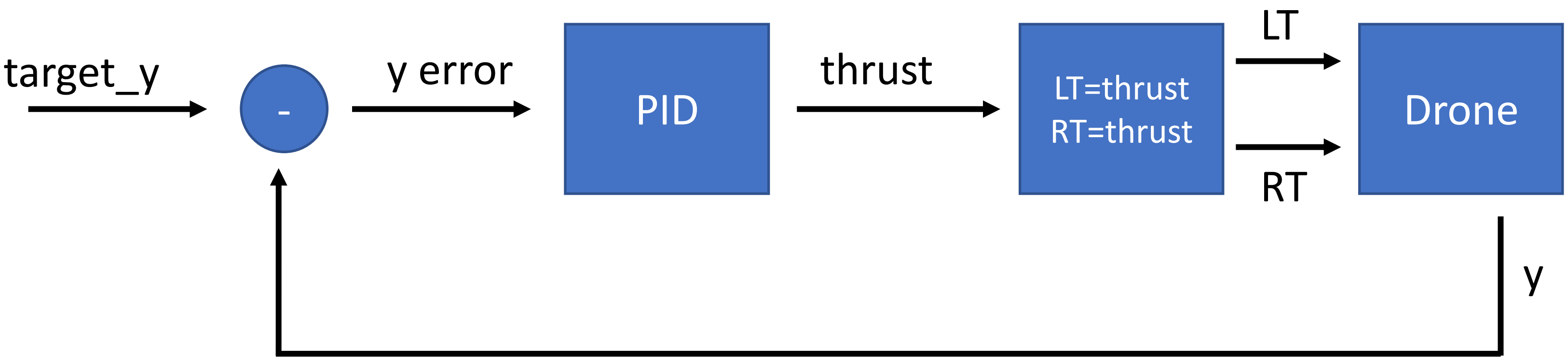
Contributed by the Committee on Industrial Instruments and Regulators of the Process Industries Division and presented at the Annual Meeting, New York, N. Y., December 1-5, 1941, of The American Society of Mechanical Engineers.



2D Drone exercise

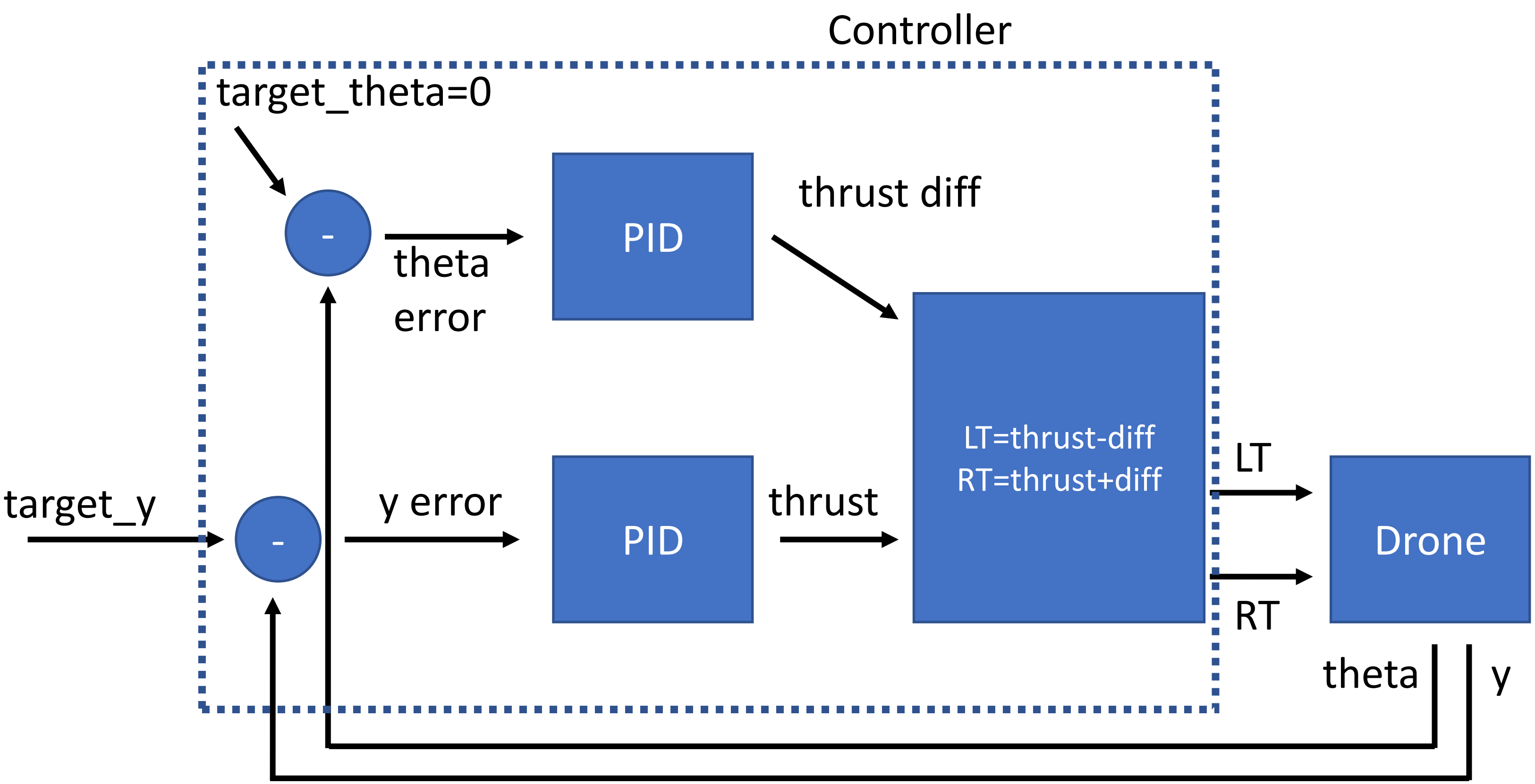
See relevant code on iCorsi

Height control

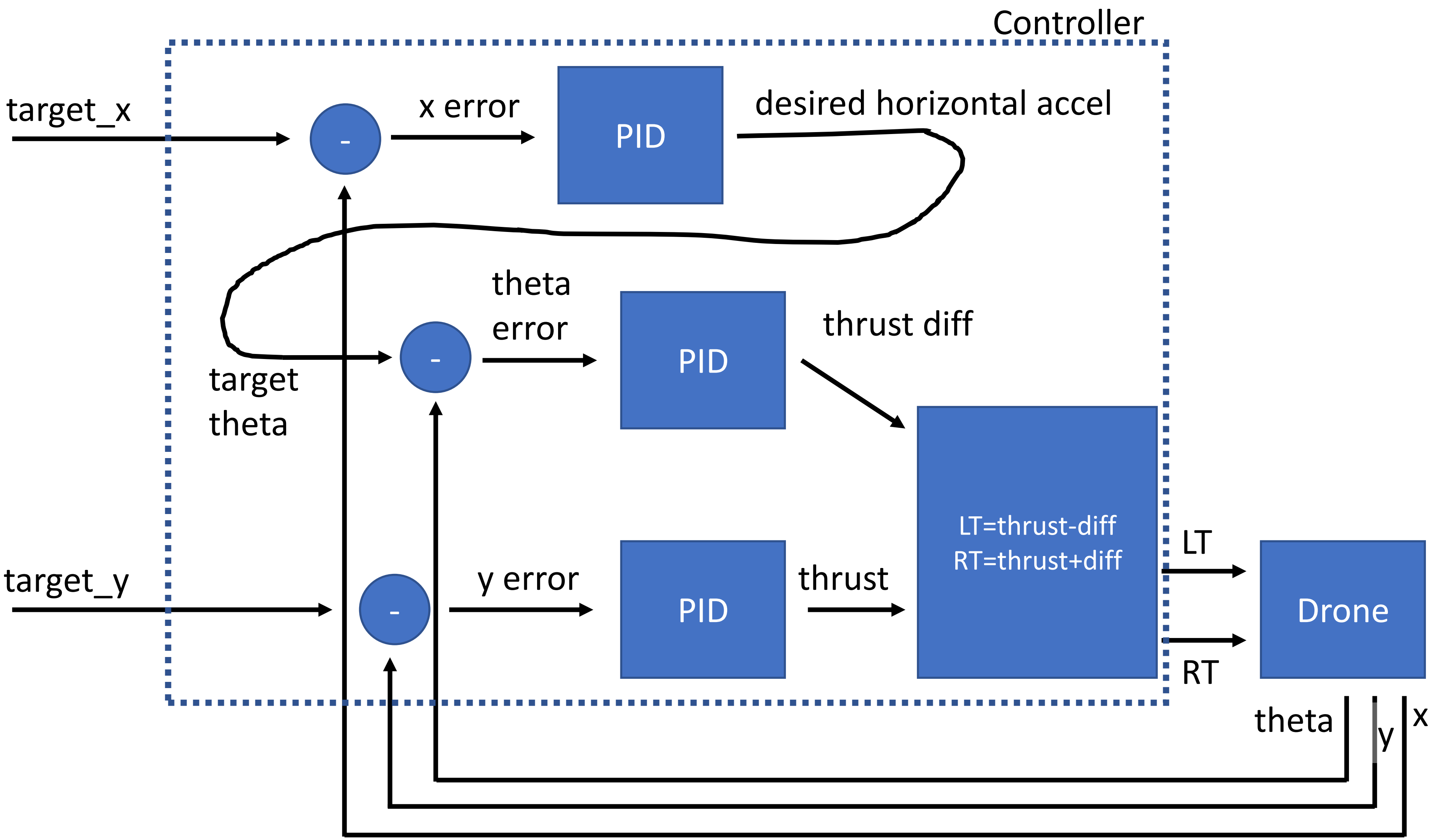


Assumes that drone starts and stays perfectly horizontal

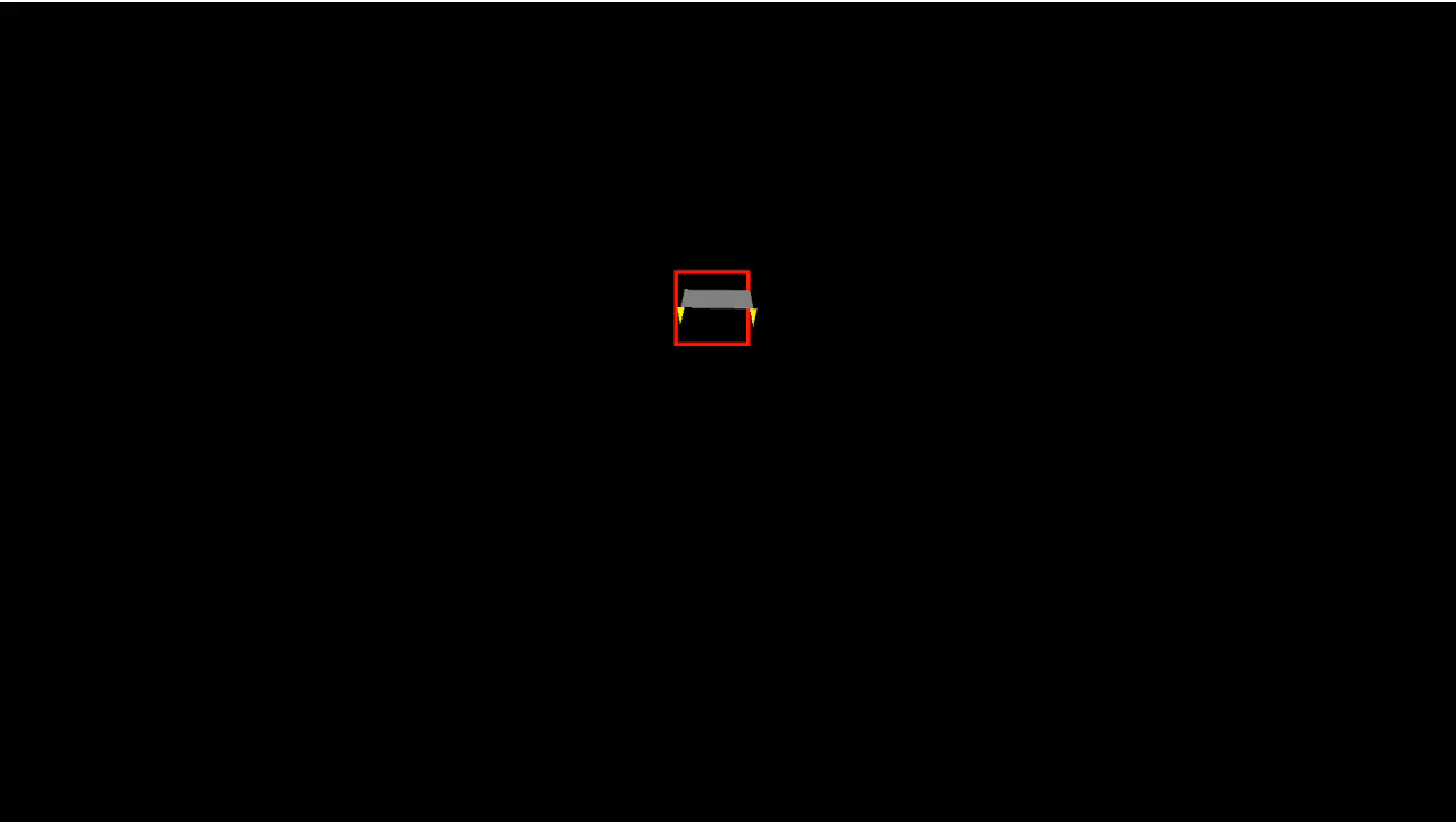
Height and attitude control



Position control



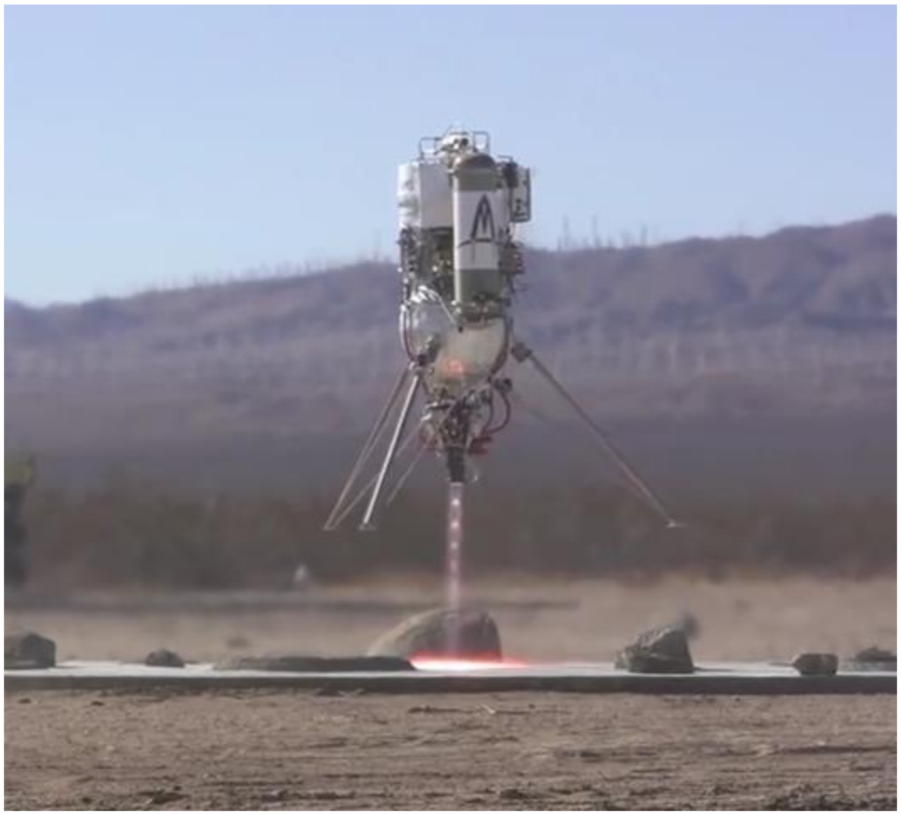
Position control behavior



Your turn! Choose one point

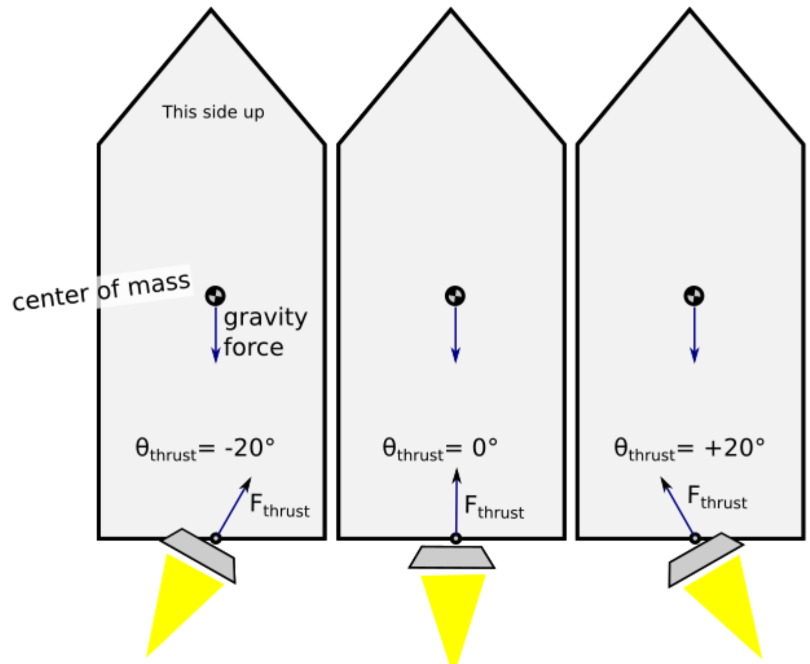
- Improve the controller we developed
  - When the target is far, the drone often spins out of control. Try limiting the desired_theta to sane values to make the drone safer!
  - When the drone is trying to ascend or descend a lot, it loses the ability to control its orientation (why?). Can you fix this behavior?
- Check what happens when…:
  - The mass of the drone is different than 1kg: change DroneViz.spawn_drone() and find out. Does your controller still work?
  - One of the thrusters is defective, for example it does not fire for 20% of the timesteps at random. Does the controller still work?
  - There is wind, which you can model as a constant horizontal force acting on the drone (e.g. 5 Newtons). How does the controlled drone behave? Change Drone2D.step(), implement wind, and find out.

Exercise (difficult): thrust vectoring

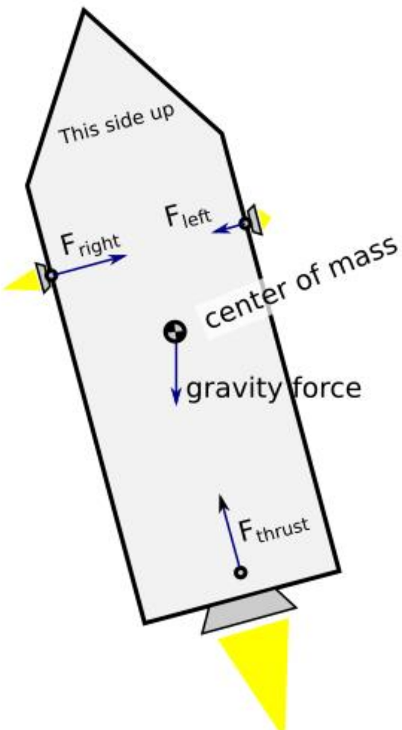


https://youtu.be/Rn6xIfY_3zM
Masten Space Systems
Xoie hovering rocket robot

Modify the simulation to consider a rocket controlled by a single engine, using thrust vectoring (changes the direction of the thrust)



Horizontal thrusters



https://youtu.be/Wn5HxXKQOjw
The Spacex Falcon 9 uses both thrust vectoring and horizontal thrusters for attitude control (see full video for more details)