Force Control

Niklas Fiedler

May 23, 2019

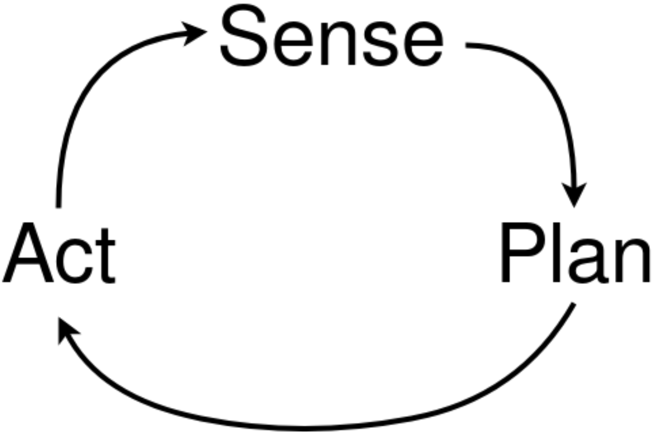
Outline I

Bibliography

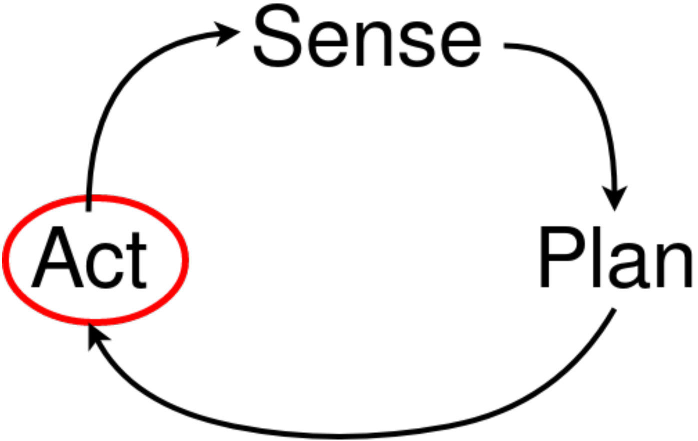
Mainly based on the following works:

- Modern Robotics - Mechanics, Planning, and Control (Kevin M. Lynch and Frank C. Park)
- Introduction to Robotics - Mechanics and Control (John C. Craig)
- Force Control in Robotics (Luigi Villani)

Sense - Plan - Act



Sense - Plan - Act



Force Control

Acting based on which input?

- On/Off
- Position
- Velocity
- Force
- Temperature
- Combination of multiple variables

Controller

goal $\longrightarrow$ output

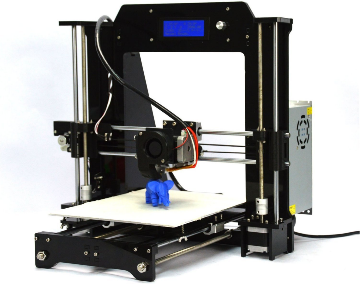
Controller

Control Systems in Robots

Open Loop Control

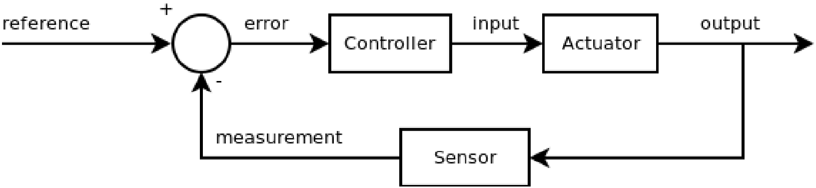
Controlling independent of process variables

- timer
- stepper motors

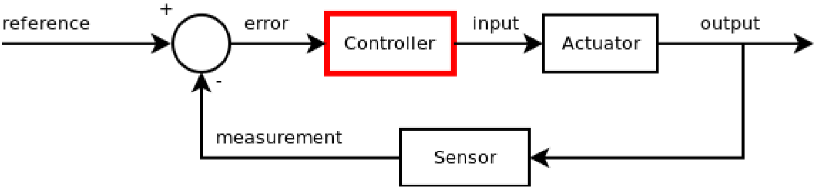


Control System Application

Closed Loop Control



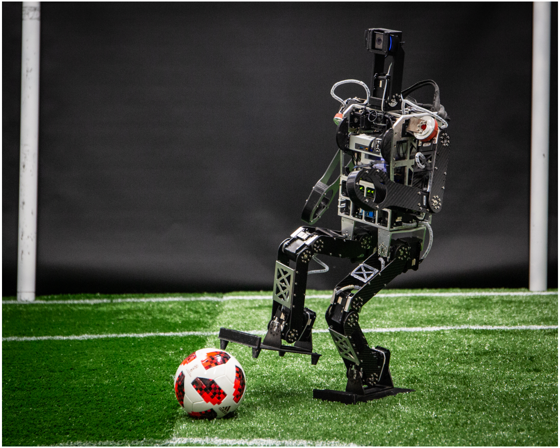
Closed Loop Control



Bang-Bang Control

- switches between two states
- hysteresis

PID Controller Application



PID Controller Application

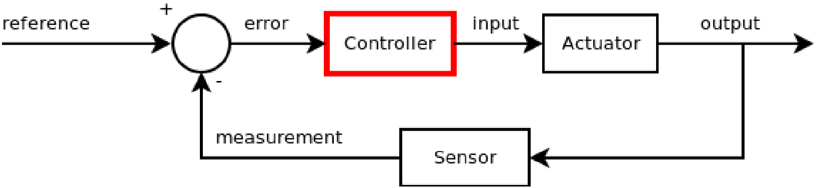
PID-Controller

Proportional Integral Derivative Controller

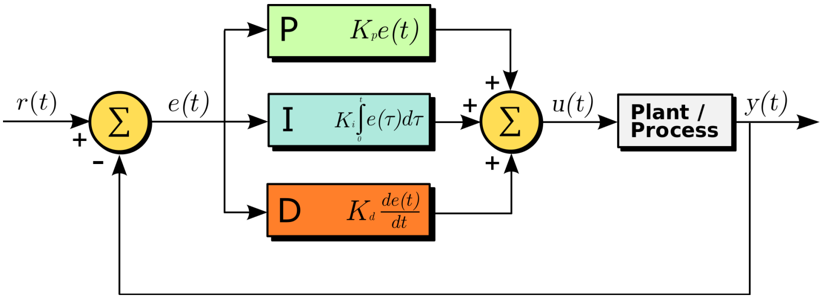
- most widely used controller concept
- originally developed for ships
- first formulation in 1922

PID-Controller

closed loop control



PID-Controller



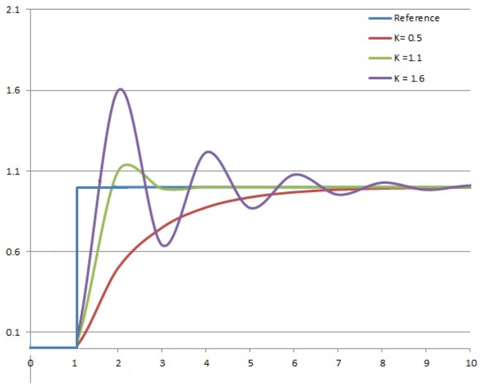
https://en.wikipedia.org/wiki/PID_controller#/media/File:PID_en.svg

Proportional Term

$$P_{out} = K_p e(t)$$

- P_{out} linearly proportional to the error $e(t)$
- correction controlled by gain K_p
- output of a proportional controller solely usable

Effect of K_p



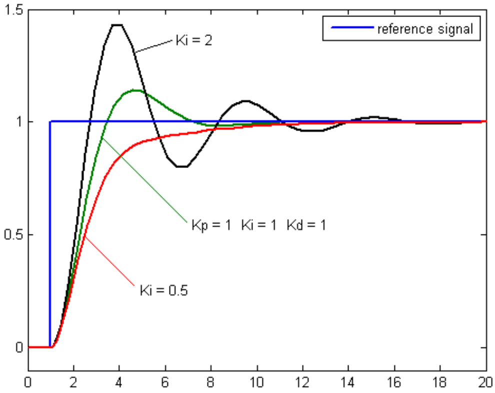
https://upload.wikimedia.org/wikipedia/commons/a/a3/PID_varyingP.jpg

Integral Term

$$I_{out} = K_i \int_0^t e(\tau) d\tau$$

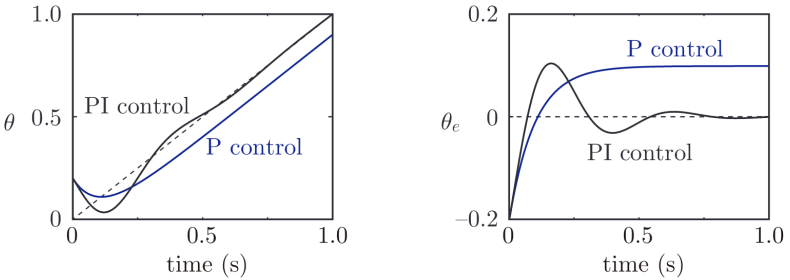
- I_{out} grows with the error summed up over time
- controlled by gain K_i
- grows faster if the error is reached slowly
- output of a integral term solely usable
- used to handle load in the movement

Effect of K_i



https://upload.wikimedia.org/wikipedia/commons/c/c0/Change_with_Ki.png

P vs PI

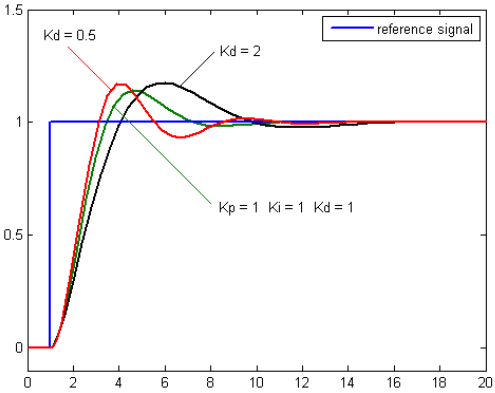

1.0
0.5
0
θ
PI control
P control
0
0.5
1.0
time (s)
0.2
0
−0.2
θ_e
P control
PI control
0
0.5
1.0
time (s)

Derivative Term

$$D_{out} = K_d \frac{de(t)}{dt}$$

- D_{out} linearly proportional to the change of the error $e(t)$
- controlled by gain K_d
- output of a derivative term NOT solely usable
- used to reduce overshoot

Effect of K_d



https://en.wikipedia.org/wiki/PID_controller#/media/File:Change_with_Kd.png

Proportional (or P-) Controller

$$P_{out} = K_p e(t)$$

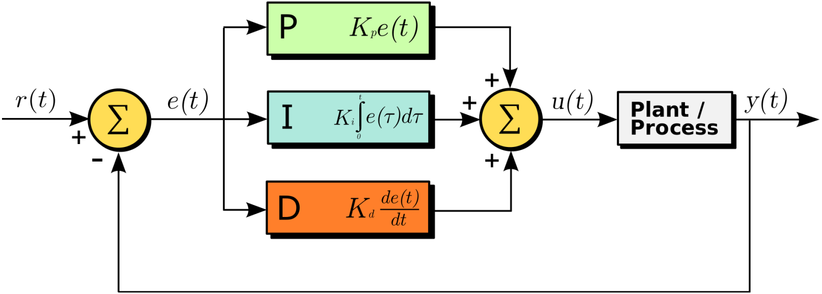
PI-Controller

$$PI_{out} = K_p e(t) + K_i \int_0^t e(\tau) d\tau$$

PID-Controller

$$PID_{out} = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}$$

PID-Controller



https://en.wikipedia.org/wiki/PID_controller#/media/File:PID_en.svg

Raw Force Control

- basically the same as position control
- forces instead of positions
- abstraction which is unusual in real applications
- the environment has to provide resistance forces in each direction

Raw Force Control

without feedback:

$$\tau = \tilde{g}(\theta) + J(\theta)^T \mathcal{F}_d$$

- $\tilde{g}(\theta)$: gravitational force
- $\mathcal{F}_d$: desired wrench

Force Measurement

Usually, force is measured by force/torque sensors

- measuring occurring force on six axes
- mounted at the actuator of the robot
- generally noisy output

Raw Force Control

with feedback (PI-Controller):

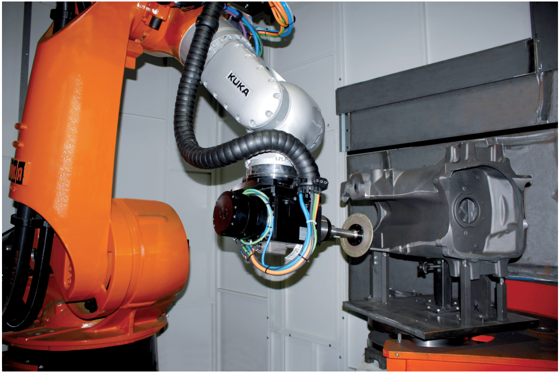
$$\tau = \tilde{g}(\theta) + J(\theta)^T \left(\mathcal{F}_d + \underbrace{K_{fp}\mathcal{F}_e}_{\text{proportional term}} + \underbrace{K_{fi} \int \mathcal{F}_e(t) \; dt}_{\text{integral term}} \right)$$

- $\tilde{g}(\theta)$: gravitational force
- $\mathcal{F}_d$: desired wrench
- velocity damping can be added for practical use

Hybrid Position/Force Control Application

https://www.kuka.com/-/media/kuka-corporate/images/industries/case-studies/schwingenmontage/flexfellow_mrk_header.jpg

Hybrid Position/Force Control Application



http://www.metalworkingworldmagazine.com/files/2013/10/Fig_09.jpg

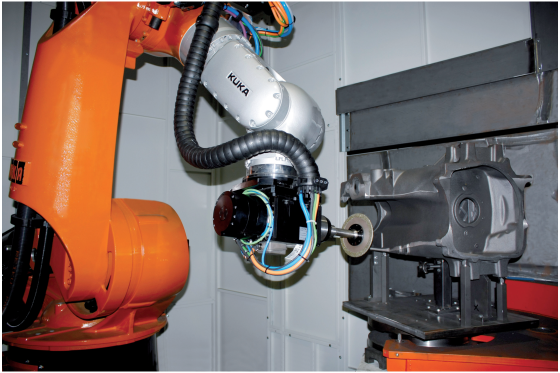
Hybrid Force Control Motivation

- object manipulation
- performing tasks on a surface
- contact with stiff surfaces
- dynamic environments (collaboration with humans)

Hybrid Force Control

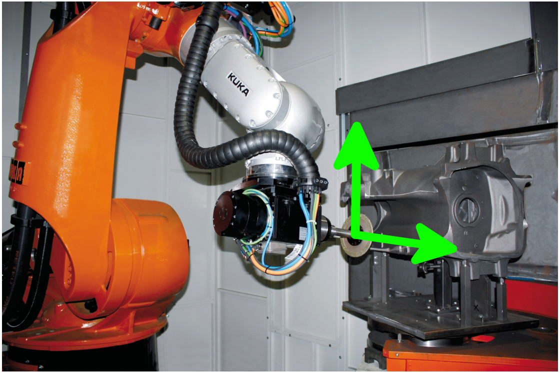
- Controlling the force applied to the environment in combination with the pose
- active compliance

Hybrid Force Control



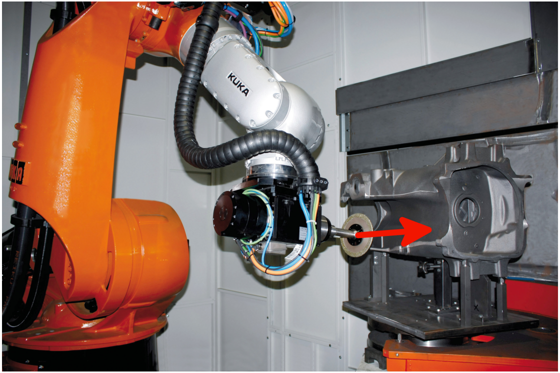
http://www.metalworkingworldmagazine.com/files/2013/10/Fig_09.jpg

Hybrid Force Control



http://www.metalworkingworldmagazine.com/files/2013/10/Fig_09.jpg

Hybrid Force Control



http://www.metalworkingworldmagazine.com/files/2013/10/Fig_09.jpg

Hybrid Force Control Formula

$$\tau = J_b^{\mathrm{T}}(\theta)\Bigg(\underbrace{P(\theta)\left(\tilde{\Lambda}(\theta)\left(\frac{d}{dt}([\mathrm{Ad}_{X^{-1}X_d}]\mathcal{V}_d) + K_p X_e + K_i \int X_e(\mathrm{t})dt + K_d \mathcal{V}_e\right)\right)}_{\text{motion control}}$$

$$+ \underbrace{(I - P(\theta))\left(\mathcal{F}_d + K_{fp}\mathcal{F}_e + K_{fi}\int \mathcal{F}_e(\mathrm{t})dt\right)}_{\text{force control}}$$

$$+ \underbrace{\tilde{\eta}(\theta, \mathcal{V}_b)}_{\text{Coriolis and gravity}}\Bigg)$$

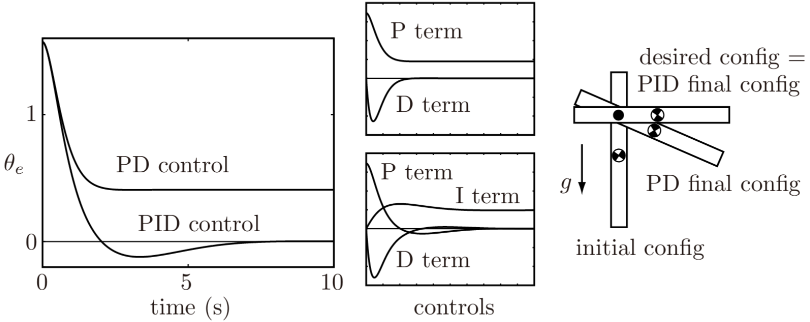
Hybrid Position/Force Control: the easy way

- setting a maximal effort in each joint applicable to reach a position
- stopping the movement when the effort is reached
- measuring the applied effort without a force/torque sensor

Image Sources

- http://www.electricshopping.com
- http://www.appliance-world.co.uk
- https://www.electronicsb2b.com
- https://make-create.org

PD vs PID


1
θ_e
0
PD control
PID control
0
5
10
time (s)
P term
D term
P term
I term
D term
controls
desired config =
PID final config
g
PD final config
initial config