Handling System Limits
PID Control with Saturation

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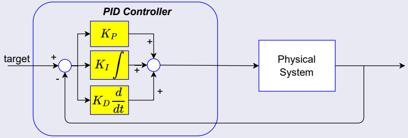
Robotic Systems

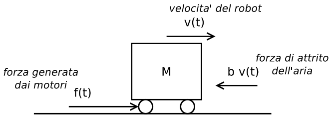
The Proportional-Integral-Derivative Controller



The Controller Output

- The output of the PID is somewhat proportional to the error (in a direct, integral o derivative “way”)
- If the error is large, the controller output may be **very large** (and also increasing in the presence of the integrator)
- But, in real life, can we provide a “driving signal” to a system that is as large as we want?
- Are systems subject to certain limits that cannot be overcome?

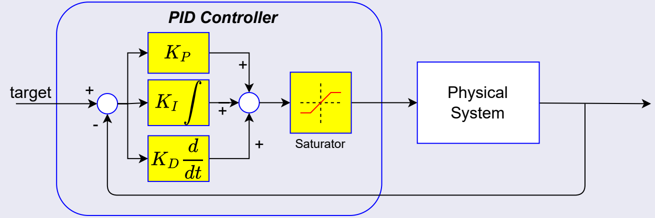
System Limits



Back to the Cart

- In the “cart example”, the force is due to the power of the motors that, in turn, is generated according to the voltage applied to motors themselves
- Increasing the voltage, increases motor power and thus the pushing force
- But can we increase such a voltage **indefinitely**?
- **NO!** There are two kind of limits:
  1. The electronics driving the motor cannot provide a voltage **greater than the power supply**
  2. Supposing that the former limit does not occur, if we overcome the limits for what the motors are designed, we easly **burn them!**

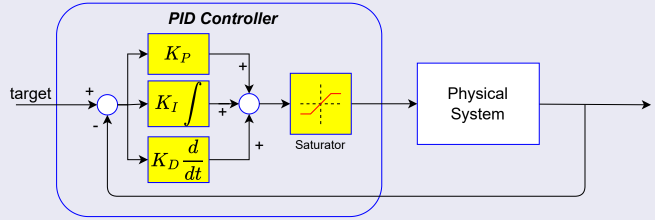
The PID Controller with Saturation



Handling Limits

- In other words, we need to **saturate** the controller output according to a certain limit OUT_{max}
- This objective is achieved by including a **saturation block** that ensure the output is always in the range $[-OUT_{max}, OUT_{max}]$

The PID Controller with Saturation



Handling Limits

- From the implementation point of view, a **saturation block** if simply a couple of "**if**s"

```
...
if output > OUT_MAX:
    output = OUT_MAX
elif output < -OUT_MAX:
    output = -OUT_MAX
# else the output is unchanged
...
```

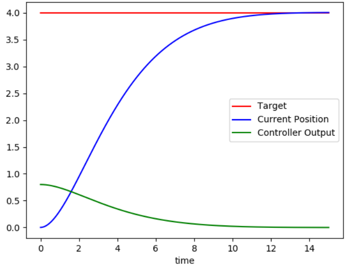
Back to the Cart

- Let us consider that in our Cart, the motors are not able to provide a push greater than 0.5 N
- Let's see the implementation of the position control **with saturation**

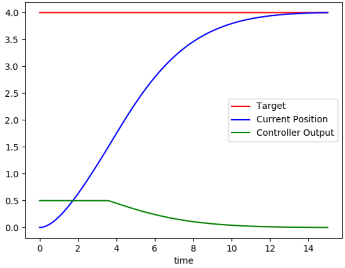
```
    ...
    self.controller = PIDSat(0.2, 0, 0, 0.5)
    # Kp = 0.2, saturation 0.5 Newton
    ...

class PIDSat:

    def __init__(self, kp, ki, kd, saturation):
        ...
        self.saturation = saturation

    def evaluate(self, delta_t, target, current):
        ...
        if output > self.saturation:
            output = self.saturation
        elif output < -self.saturation:
            output = - self.saturation
        return output
```

Cart Position Control with Saturation

Without saturation



With saturation



Speed Control with Saturation

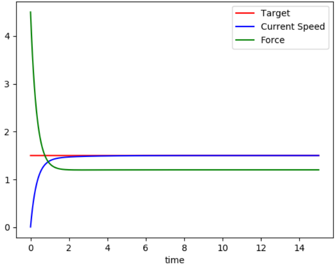
Back to the Cart

- Also in the case of speed control we must consider the presence of system limits and thus saturation
- Let's consider the cart with 0.5 *N* of maximum push
- Let's test the speed control algoritm using the same parameters of the case without saturation

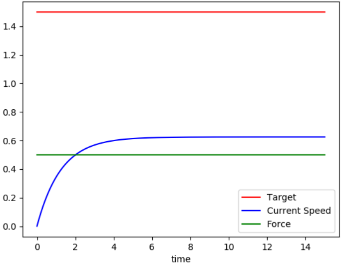
```
...
self.controller = PIDSat(3.0, 2.0, 0.0, 0.5)
# Kp = 3, Ki = 2, Sat = 0.5 N
self.target_speed = 1.5 # 1.5 m/s
...
```

Cart Speed Control with Saturation

Without saturation



With saturation (0.5 N)



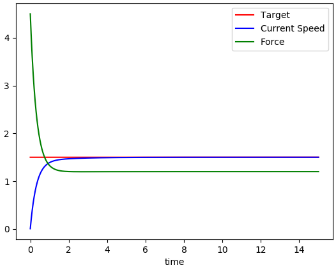
The system is constantly in saturation and there is **no way** to achieve the target speed of 1.5 m/s

Cart Speed Control with Saturation

Let's change our motors with more powerfull ones that are able to provide up to 2 N

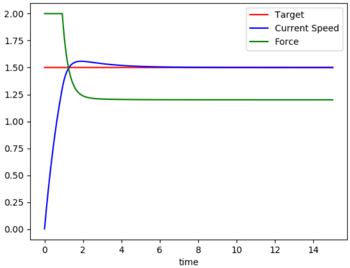
Without saturation

$K_P = 3, K_I = 2$



With saturation (2 N)

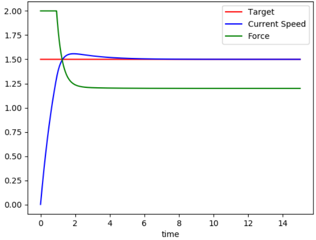
$K_P = 3, K_I = 2$



It works!! But...an overshot appeared!!! Why?

Speed Control with Saturation

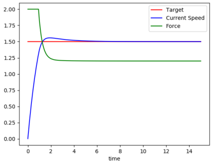
With saturation (2 N)
$K_P = 3, K_I = 2$



The Overshot...

- Even if we used the same parameters, in the presence of saturation the overall system is different, so a different behaviour is expected
- Above all, the saturator is a **non-linear block**
- Indeed, the overshot is due to the integrator that accumulates the error

Speed Control with Saturation



The Anti-Wind-up Optimisation

- Accumulating the error is necessary to obtain an adequate long-term output able to let the system reach the target
- But, when we are in the "saturation area", does it make sense to accumlate the error in any case?
- After all, since we have reached the system limits, increasing the accumulated value (above the system limits) does not help in any way
- Worstly, if the accumulated value is **too high** (and the target is overcome) we must wait more time for its reduction (and this is the overshot!)

The Anti-Wind-up Optimisation

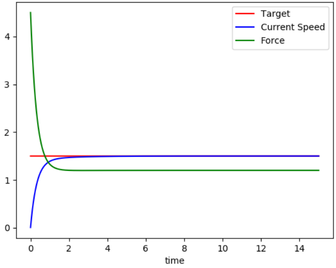
- So, let's check when we are in the saturation area and, if this is the case, do not call the integrator (see standard.py, class PIDSat)

```
def evaluate(self, delta_t, target, current):
    error = target - current
    derivative  = (error - self.prev_error) / delta_t
    self.prev_error = error

    if not(self.in_saturation):
        self.i.evaluate(delta_t, target, current)

    output = self.p.evaluate(target, current) + self.i.output + \
      derivative * self.kd

    if output > self.saturation:
        output = self.saturation
        self.in_saturation = True
    elif output < -self.saturation:
        output = - self.saturation
        self.in_saturation = True
    else:
        self.in_saturation = False
    return output
```

Cart Speed Control with Saturation

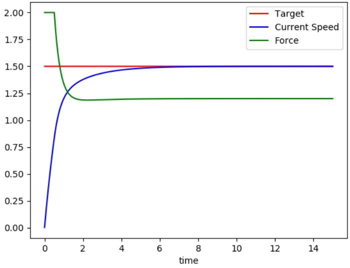
Without saturation

$K_P = 3, K_I = 2$



With saturation (2 *N*) and Anti-Wind-up

$K_P = 3, K_I = 2$



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