# Achieving High Performance from Shape Memory Alloy (SMA) Actuators

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(reporting the work of Yee Harn Teh)

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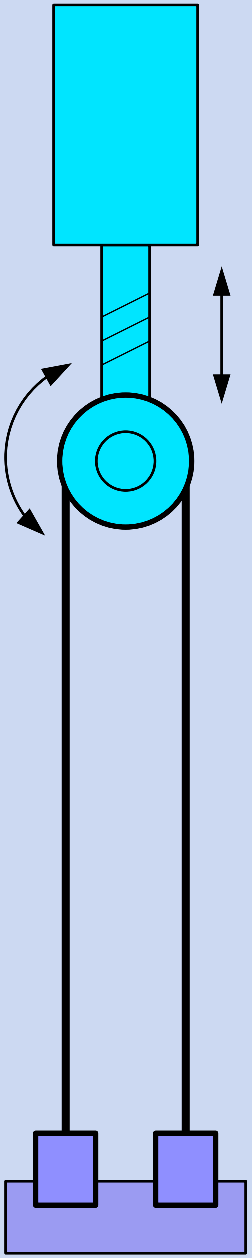
# The Testbed

precision linear stage

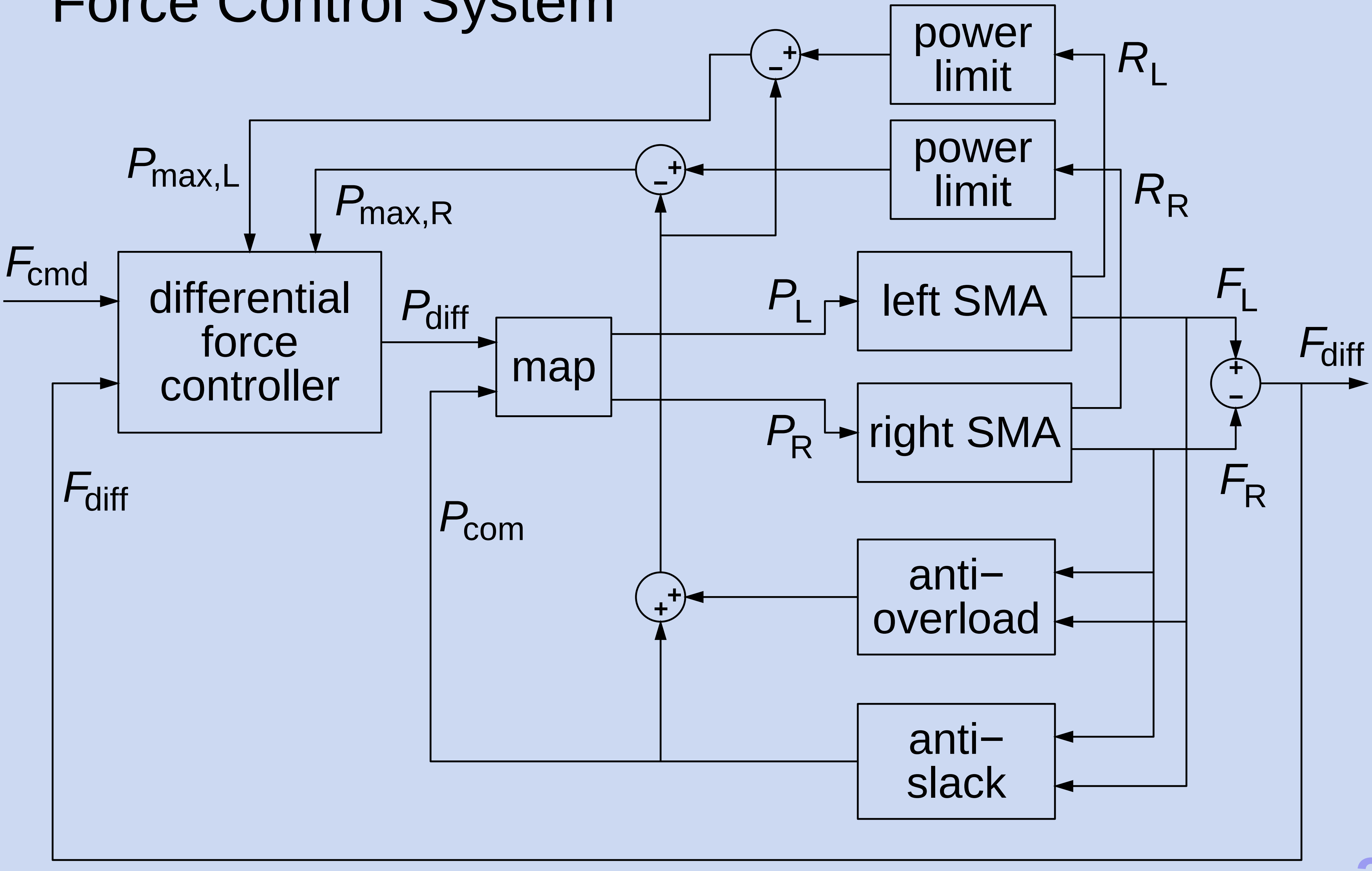
lockable pulley with
optional pendulum load

antagonistic pair
of SMA wires

load cells



# Force Control System



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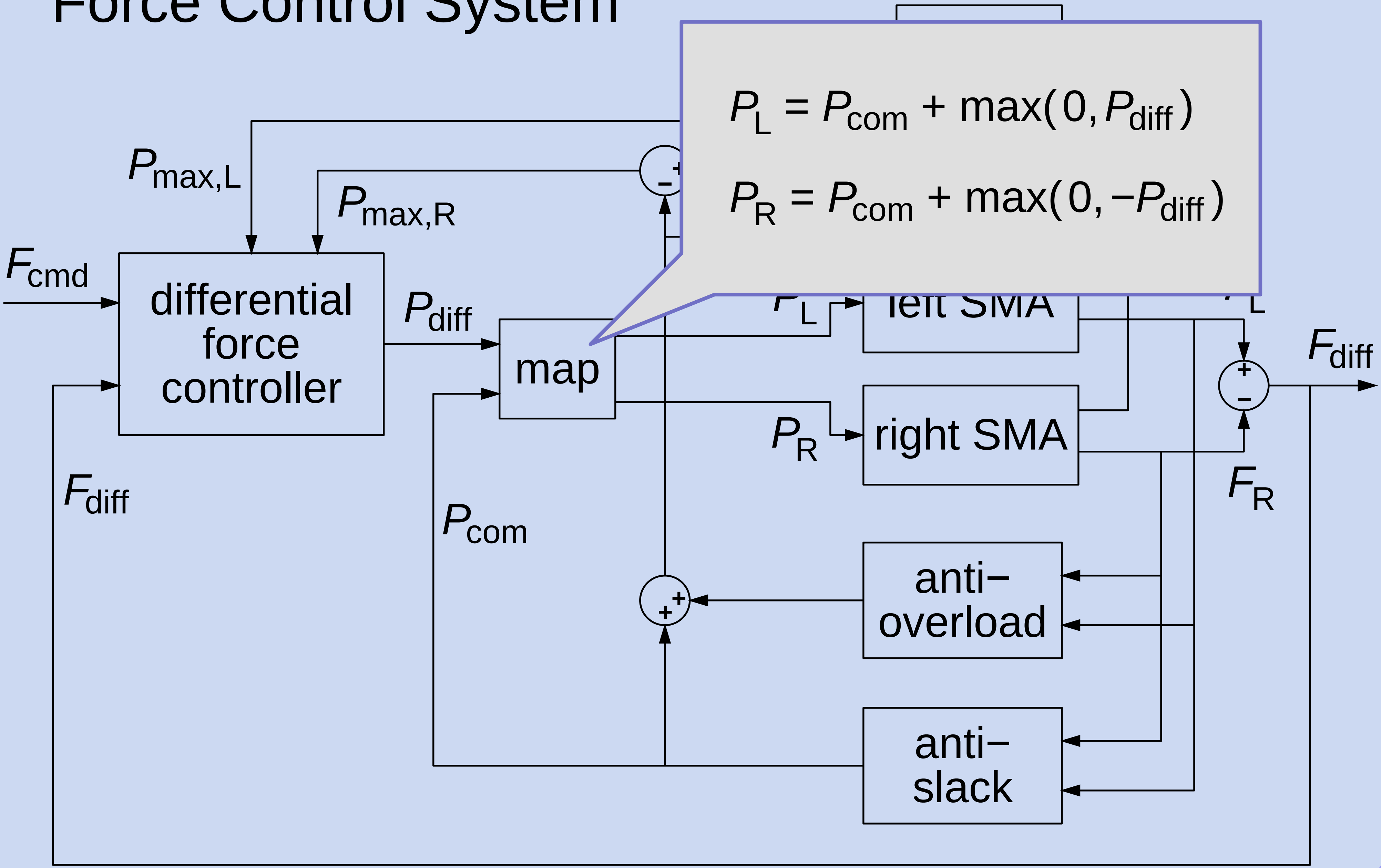
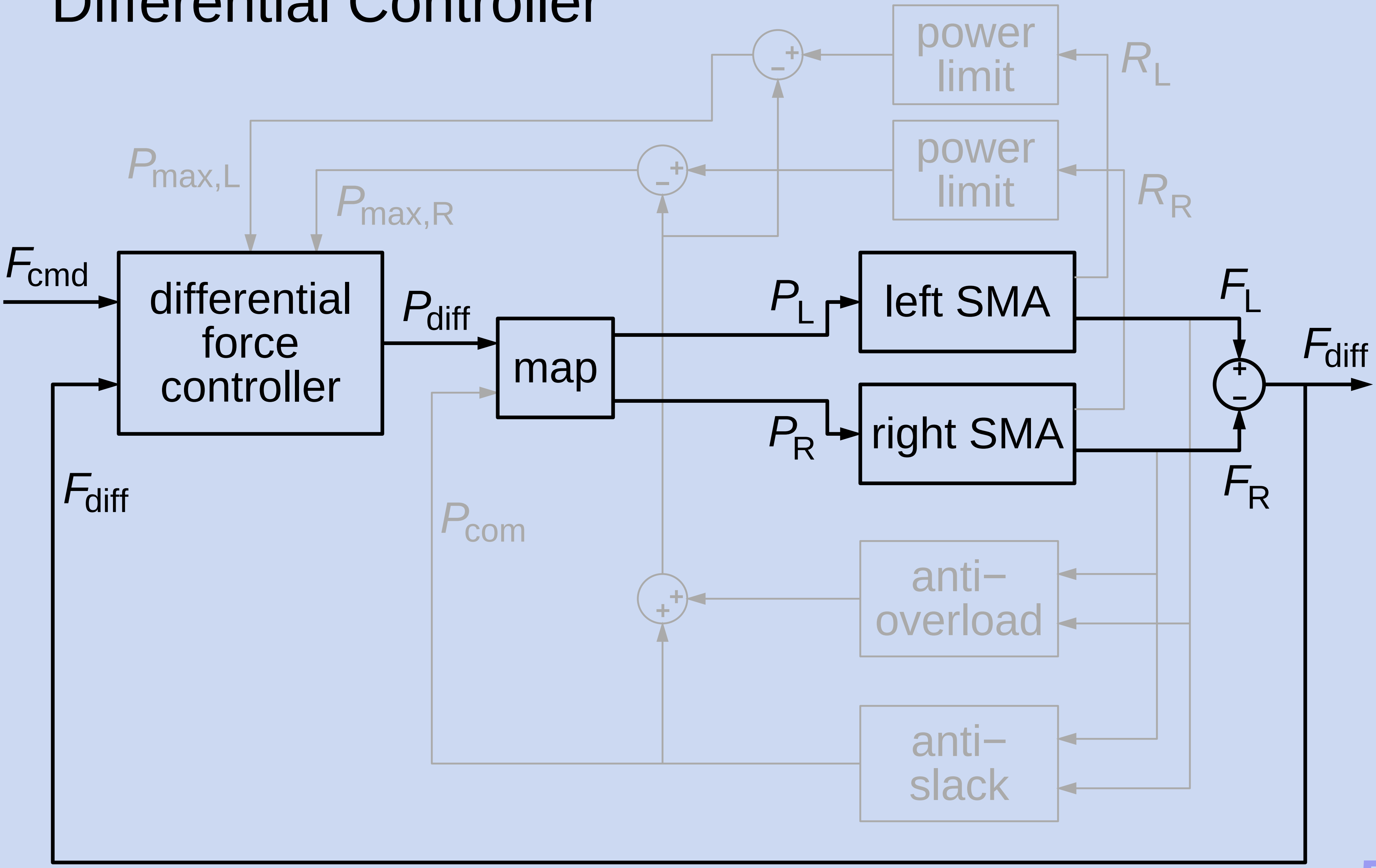


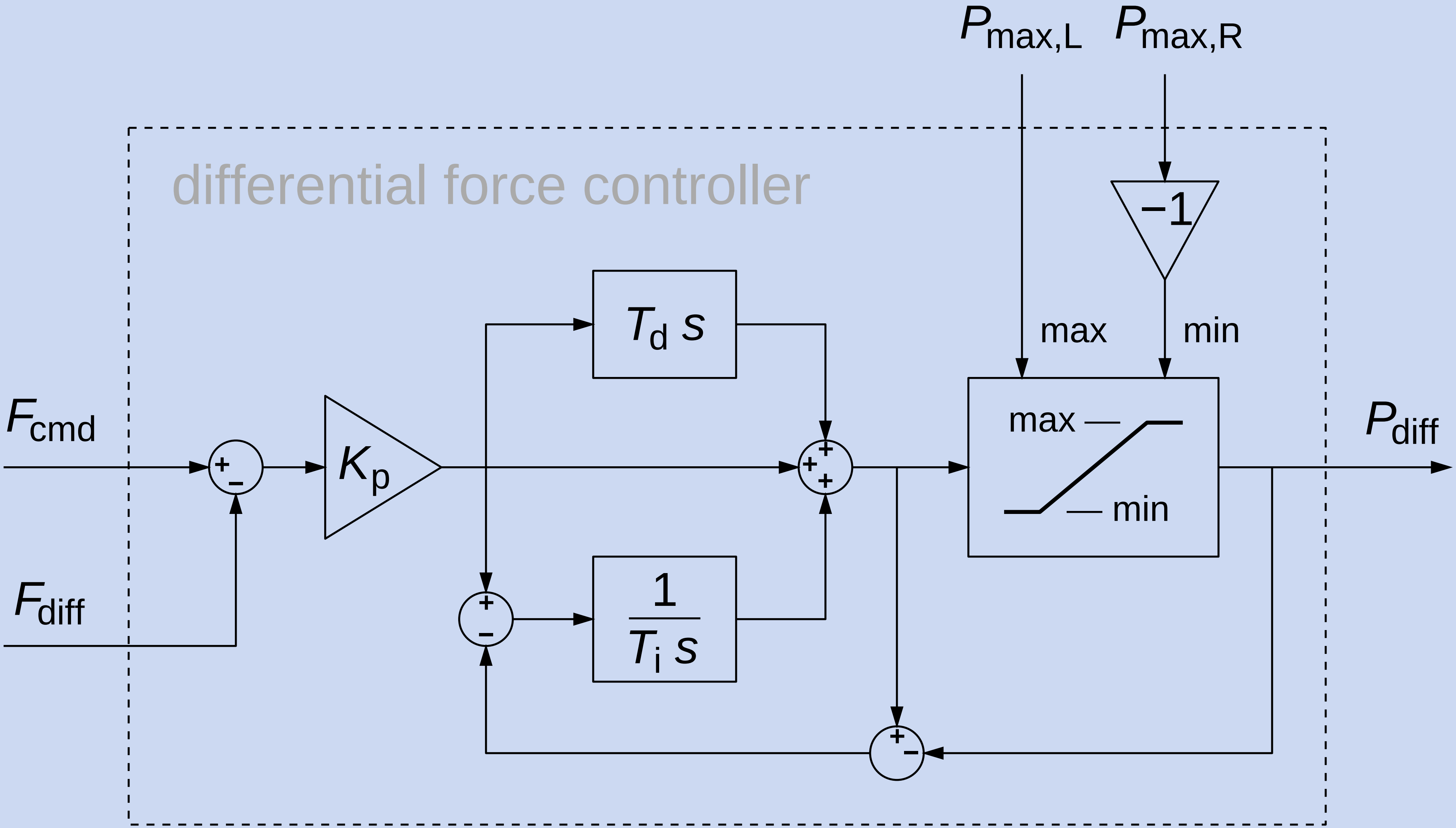

$$P_L = P_{com} + \max(0, P_{diff})$$

$$P_R = P_{com} + \max(0, -P_{diff})$$

# Differential Controller



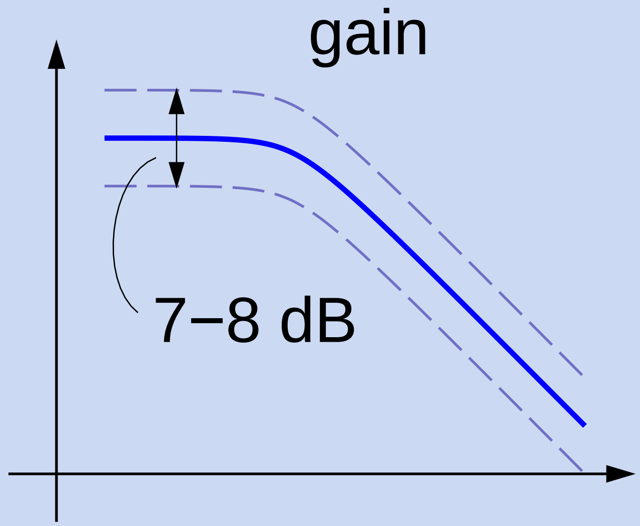
# Differential Controller

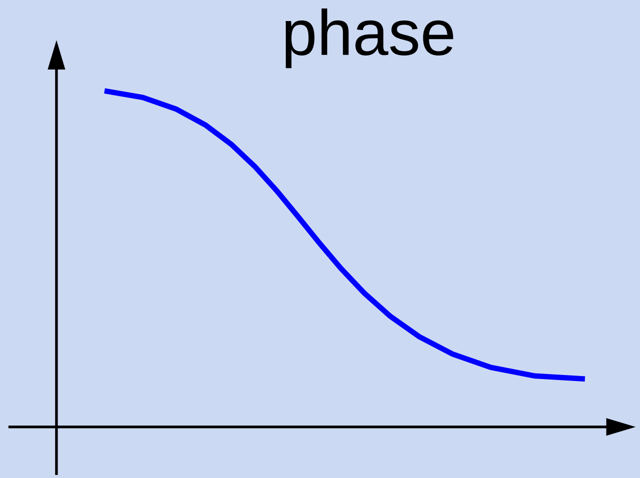


# Behaviour of the Plant

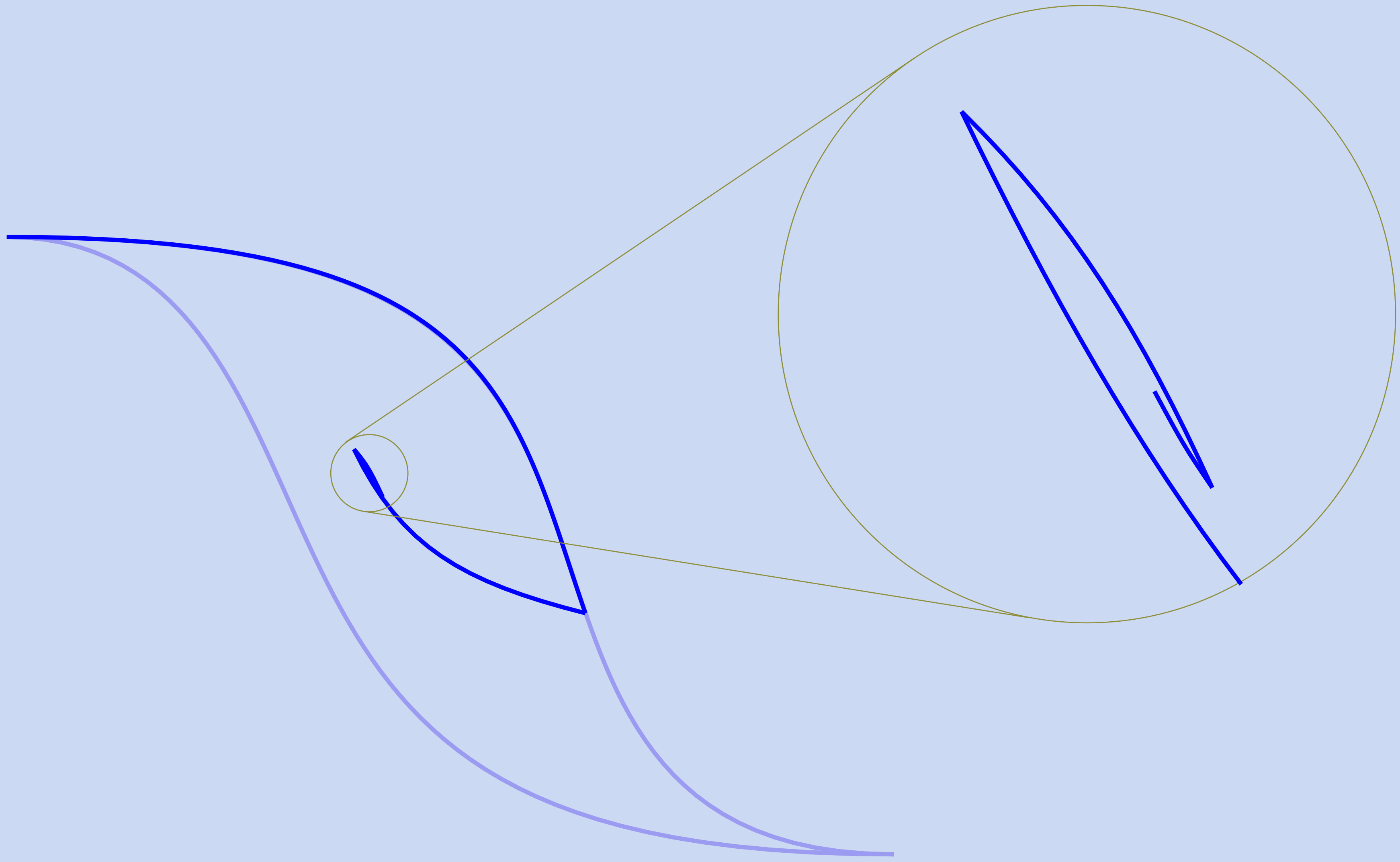
The *small−signal AC response* of nickel−titanium SMA approximates to a first−order low−pass filter.

- Gain varies with mean stress and strain in a 7−8 dB range
- Phase is *independent of stress and strain*
- Cut−off frequency varies with wire diameter



# What Happened to the Hysteresis?



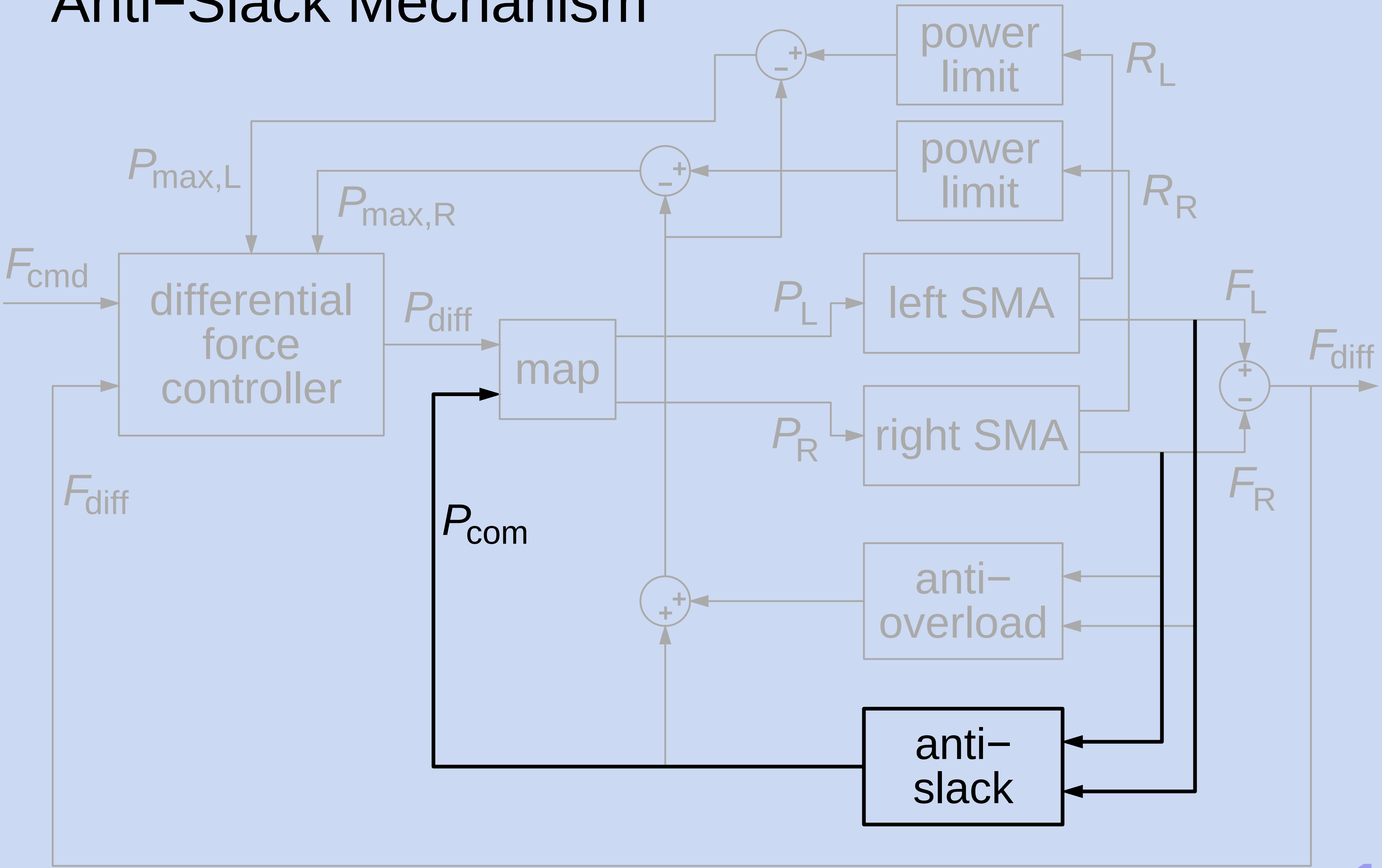
# A Problem

When Flexinol™ wires are used in an antagonistic−pair actuator, they quickly develop a *two−way shape memory effect*, in which the wires *actively lengthen* as they cool, even if the tension on the wire is zero.

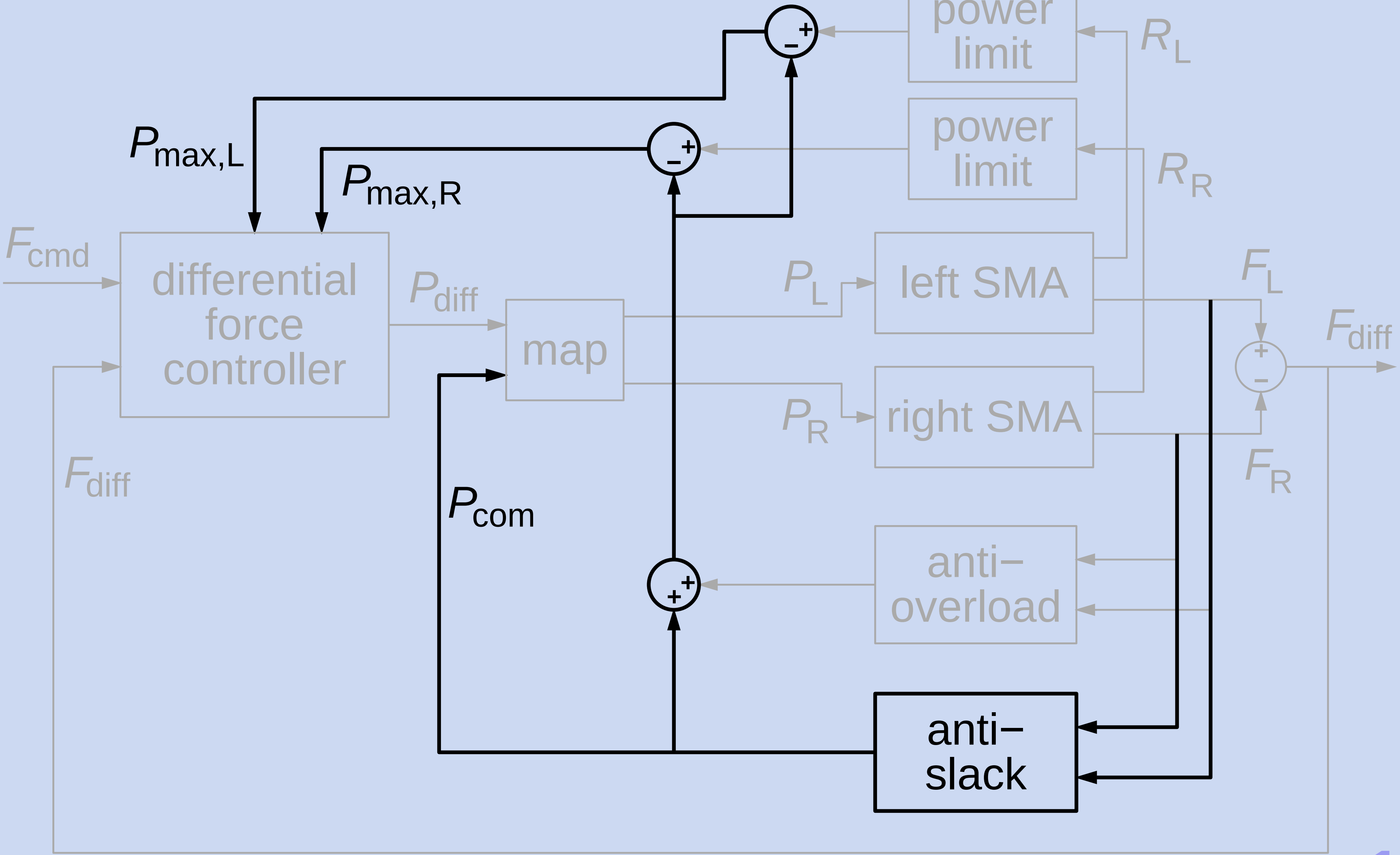
Symptom: The wires can become slack as they cool.

Remedy: An *anti−slack mechanism* that maintains a minimum tension on both wires at all times.

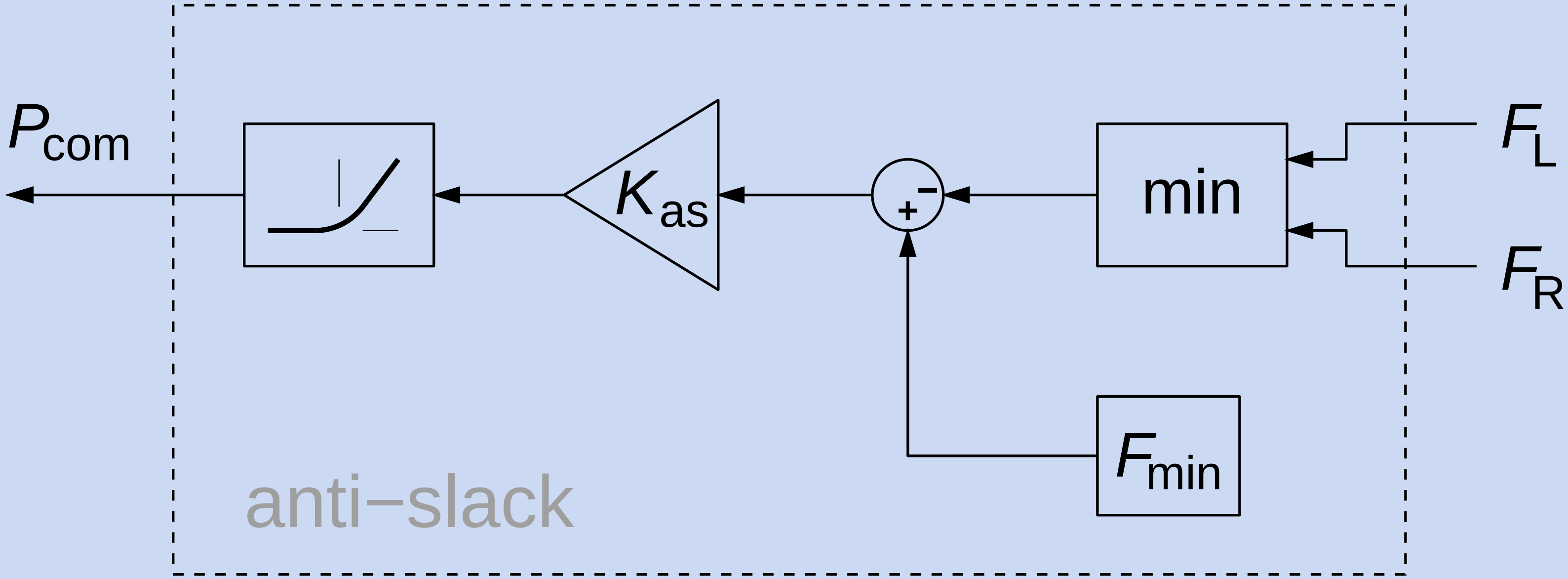
# Anti−Slack Mechanism



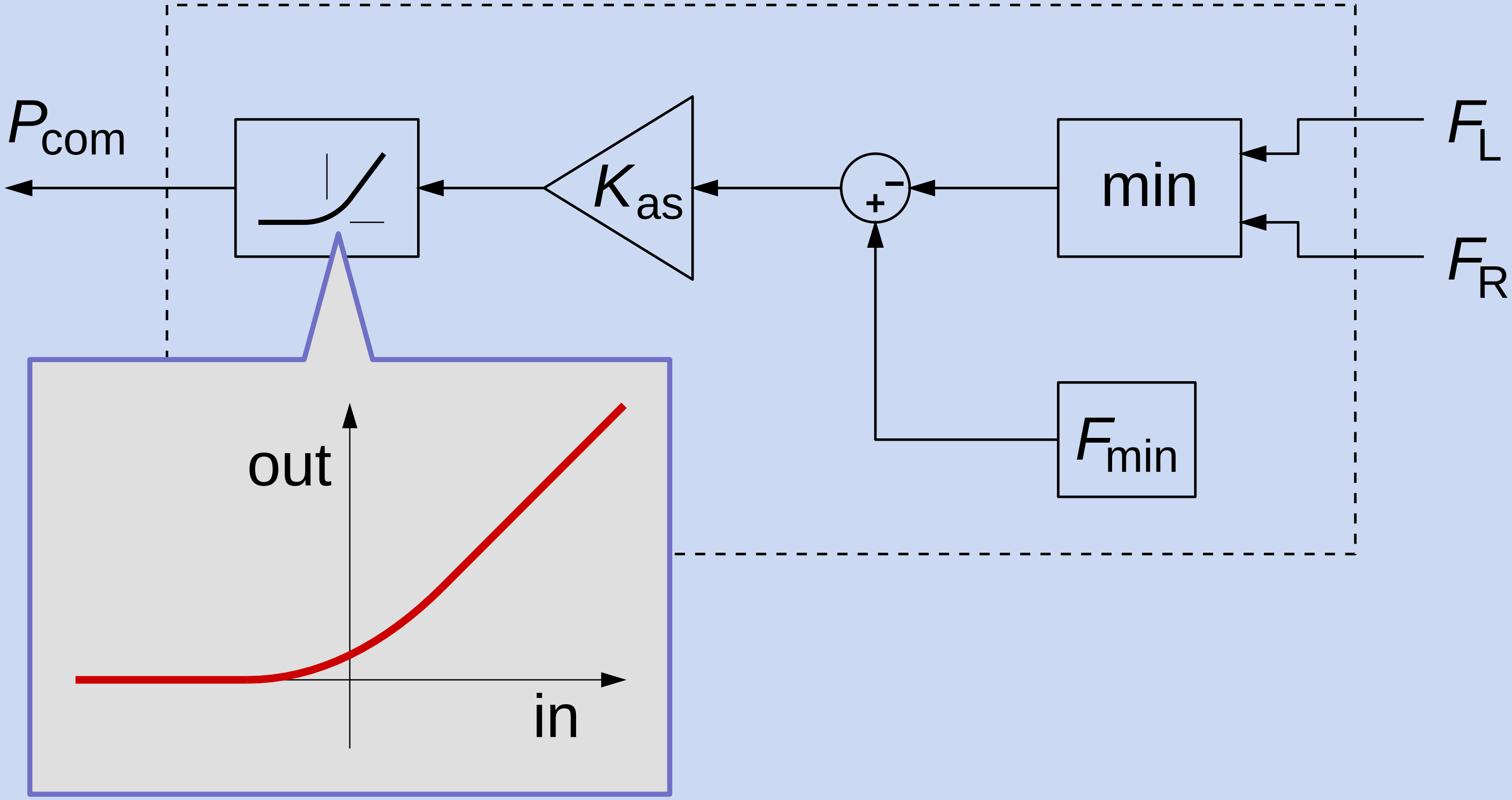
# Anti−Slack Mechanism



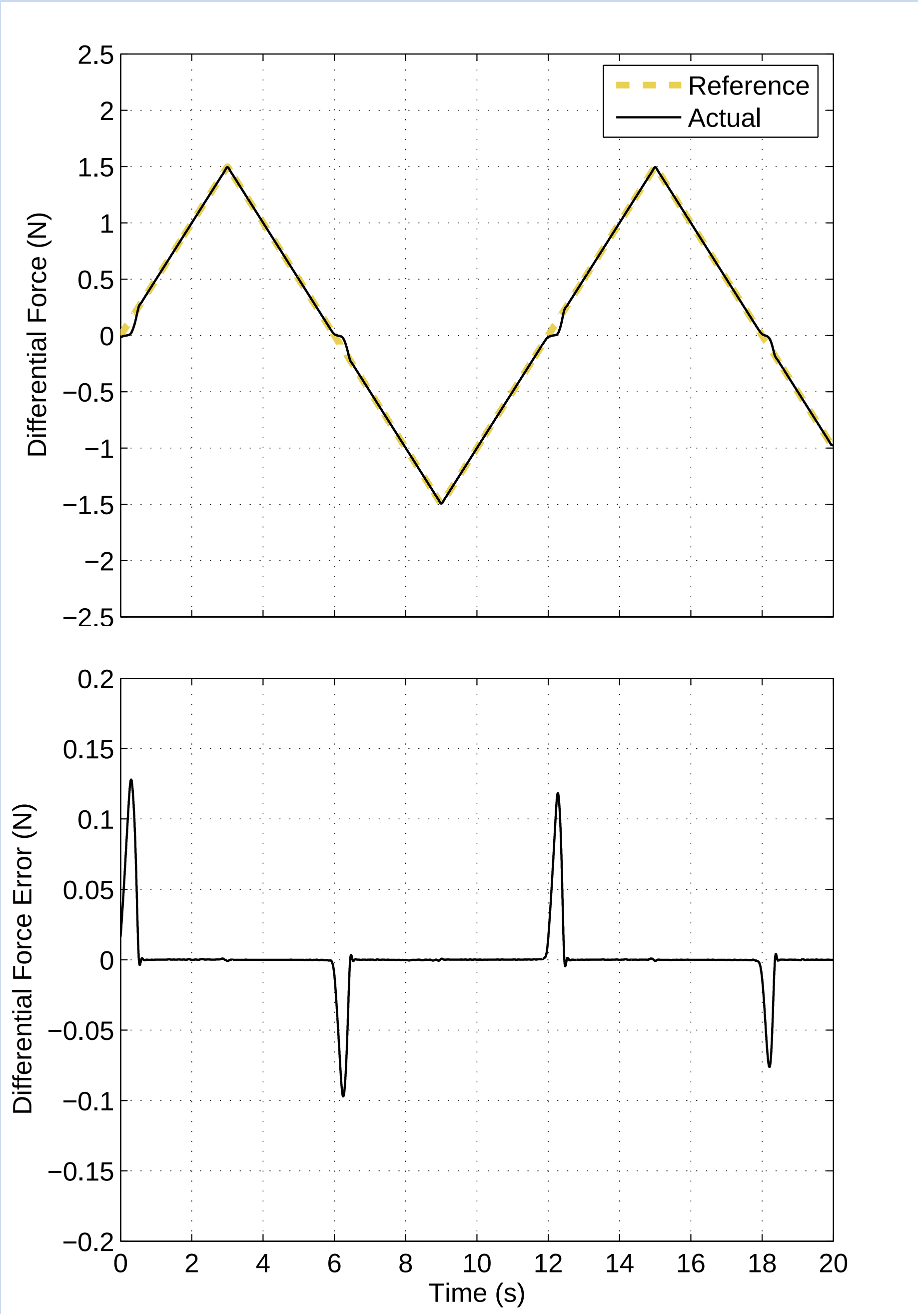
# Anti−Slack Mechanism



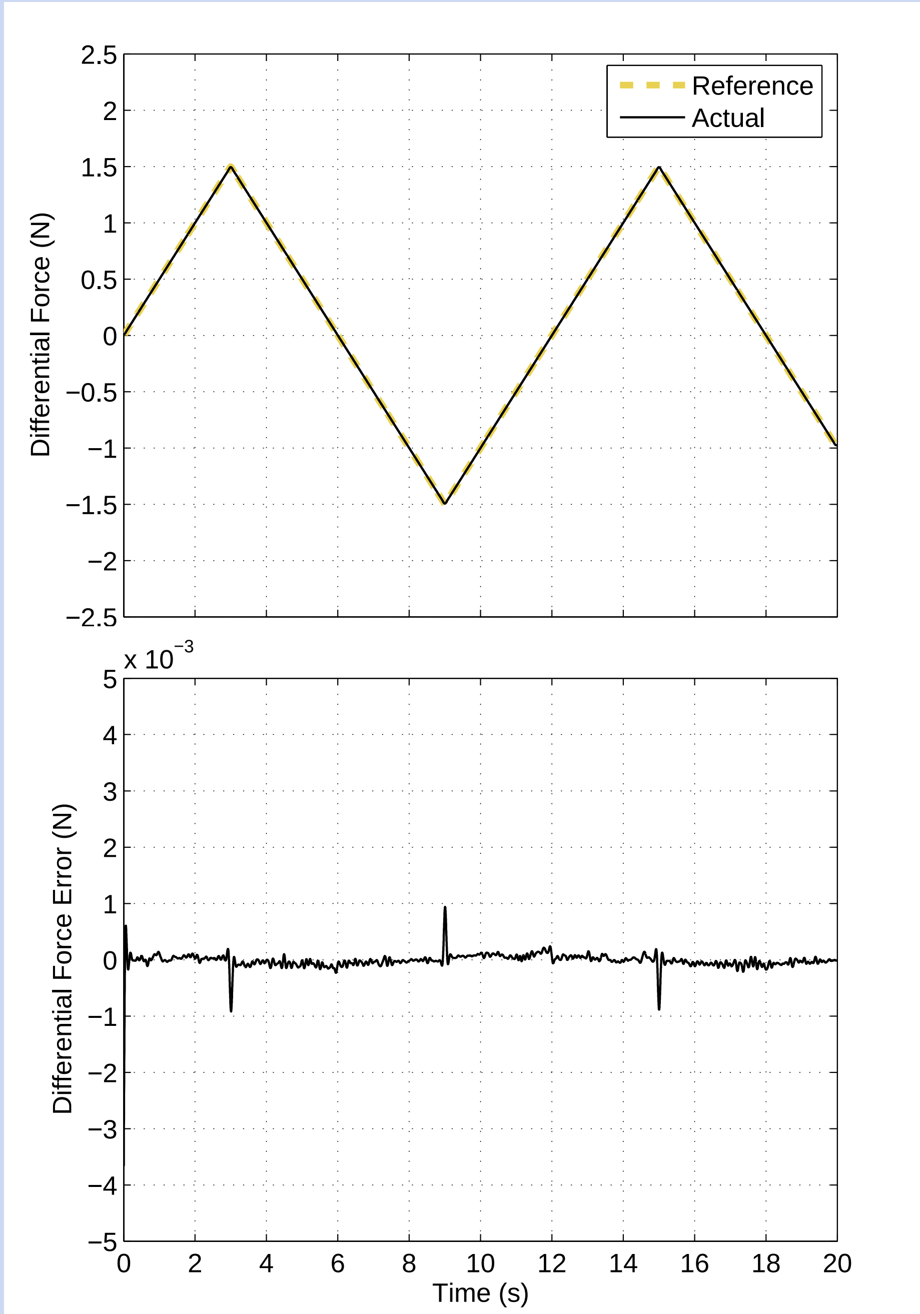
# Anti−Slack Mechanism



## without anti−slack




## with anti−slack



## Another Problem

We want the actuator to be as fast as possible. The speed can be increased by means of

- a faster heating rate, and/or
- a faster cooling rate.

A faster heating rate is more beneficial and easier to implement.

problem: how to achieve faster heating without risk of overheating?

# Why Focus on Heating?

Excerpt from Flexinol$^{TM}$ data sheet:

| Diameter (mm) | Current (mA) | Contraction Time (sec) | Off Time 70C | Off Time 90C |
|---|---|---|---|---|
| 0.050 | 50 | 1 | 0.3 | 0.1 |
| 0.075 | 100 | 1 | 0.5 | 0.2 |
| 0.100 | 180 | 1 | 0.8 | 0.4 |

If we use the recommended safe heating currents then, for a thin wire, heating takes longer than cooling.

# Rapid Electrical Heating

To obtain a rapid response from an SMA wire, we need a heating strategy that

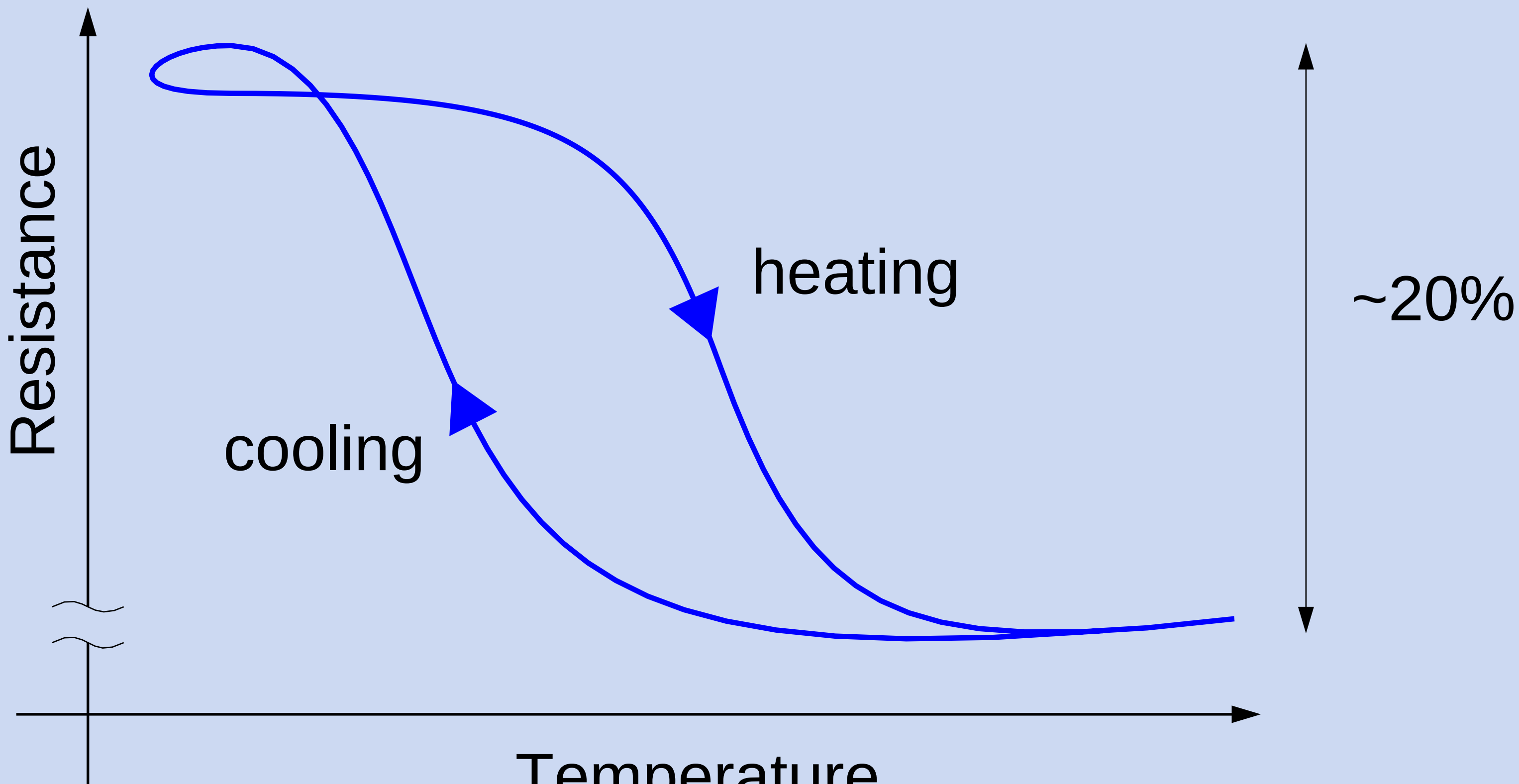
- allows *large heating powers* when there is *no risk* of overheating, but
- allows only a *safe heating power* when there *is a risk* of overheating.

This can be accomplished by

- *measuring the electrical resistance* of the wire, and
- calculating a *heating power limit* as a function of the measured resistance

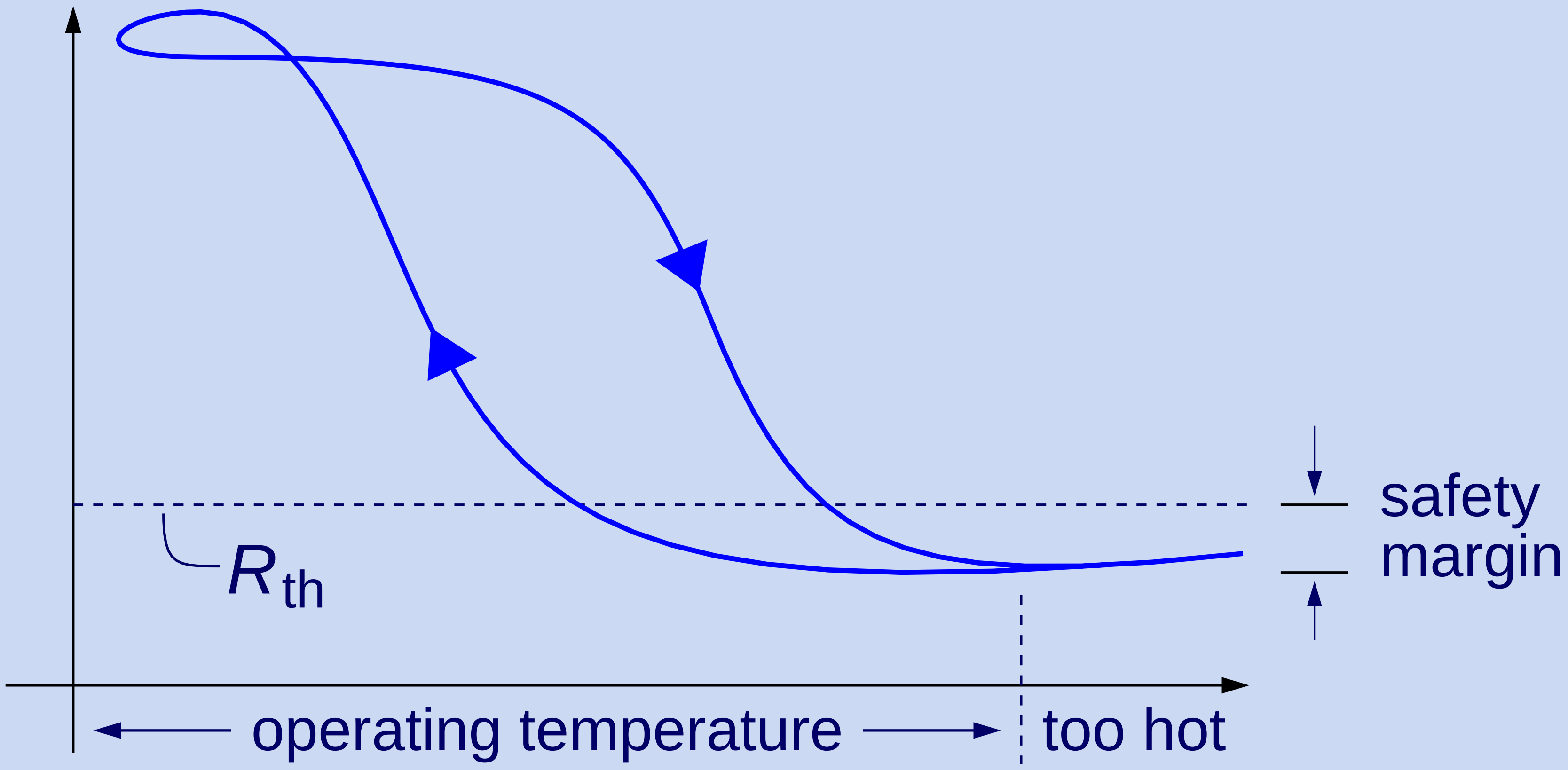
# Electrical Resistance vs. Temperature

The electrical resistance (of nitinol) varies with the martensite ratio, and therefore also with temperature, because the resistivity of the martensite phase is about 20% higher than the resistivity of the austenite phase.



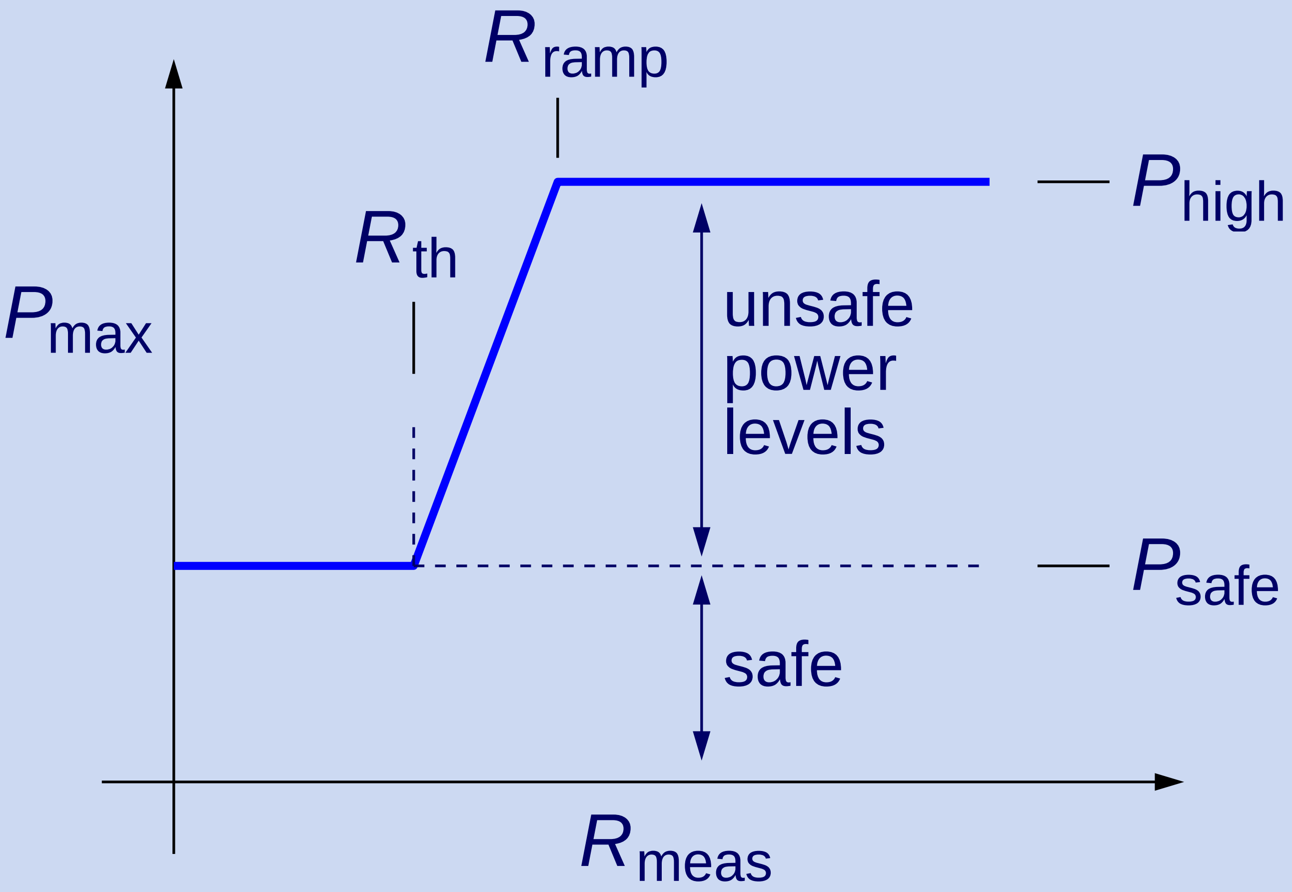
# Calculating the Power Limit

1. Choose a threshold resistance, $R_{th}$, which is equal to the hot resistance of the wire plus a safety margin.

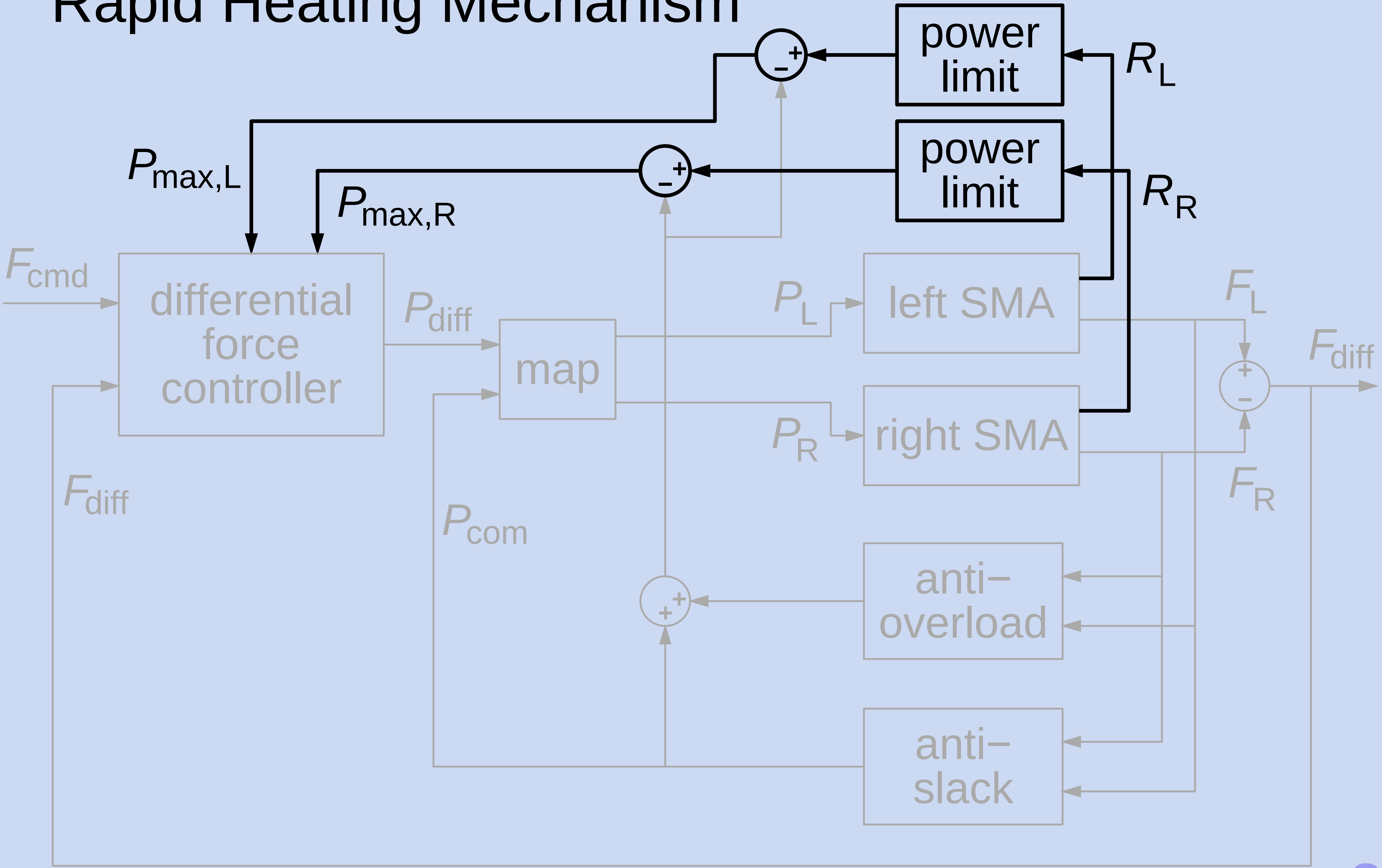


# Calculating the Power Limit

2. Calculate the power limit, $P_{max}$, as a function of the measured resistance, $R_{meas}$.

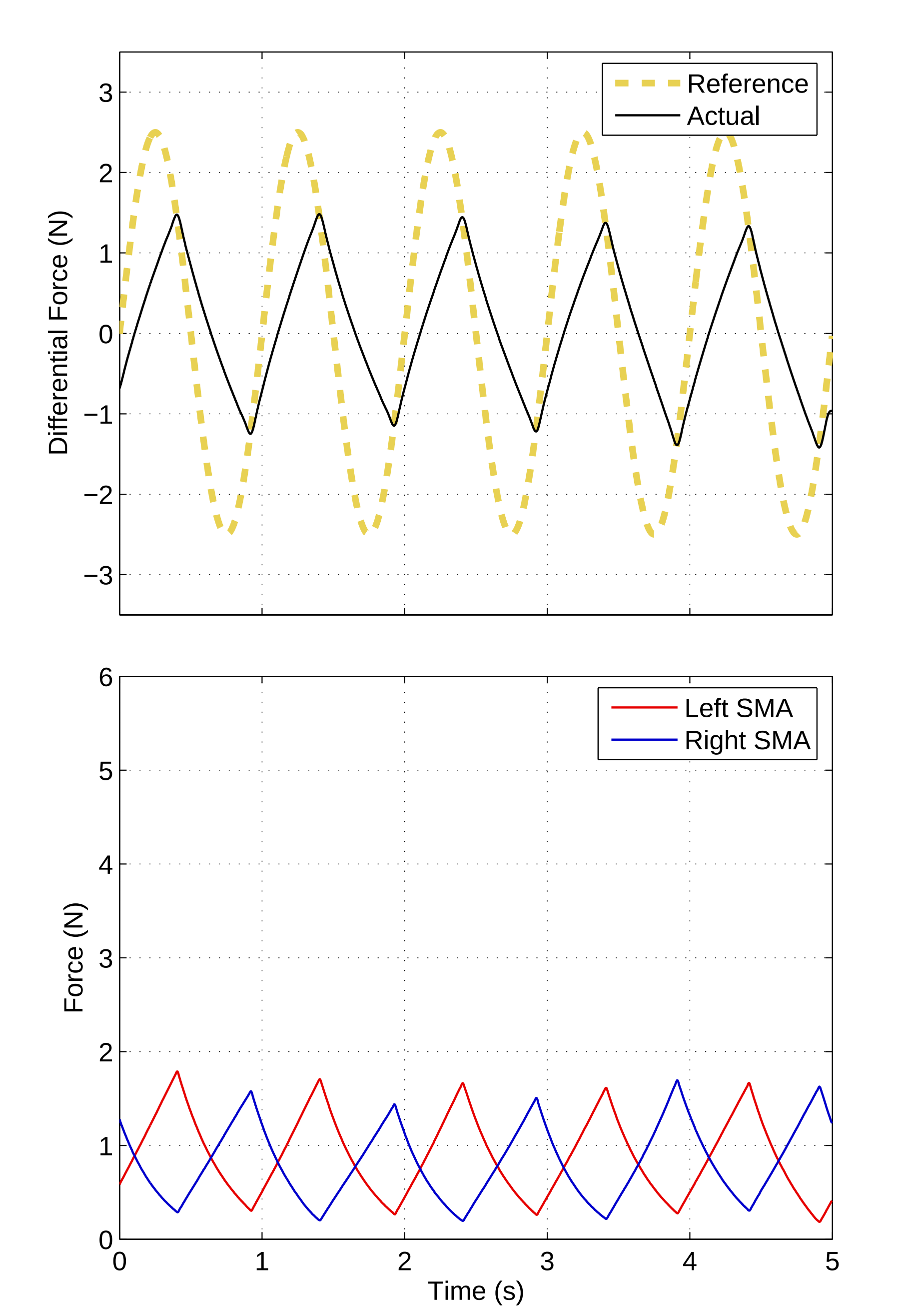


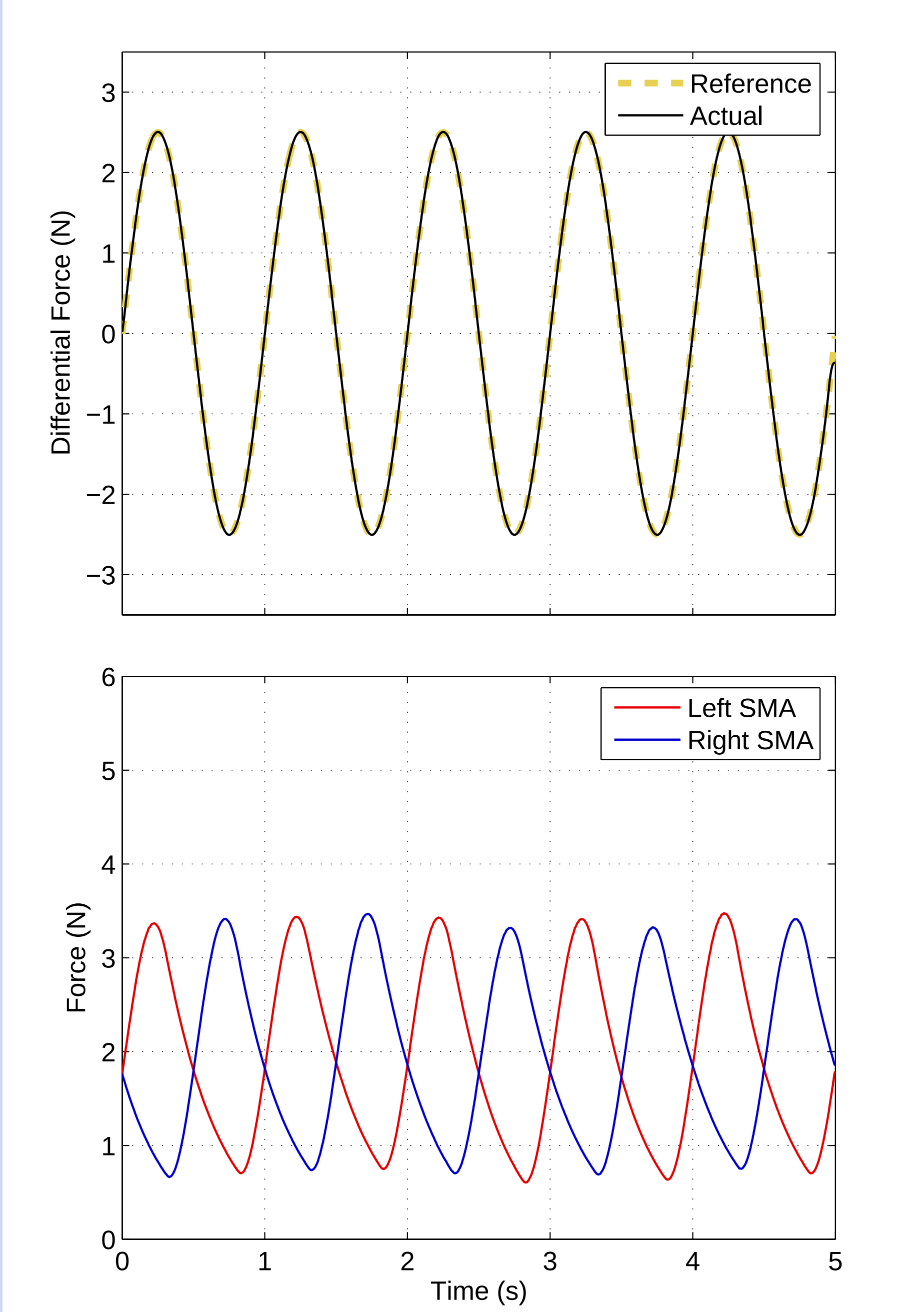
# Rapid Heating Mechanism



## without rapid heating

## with rapid heating



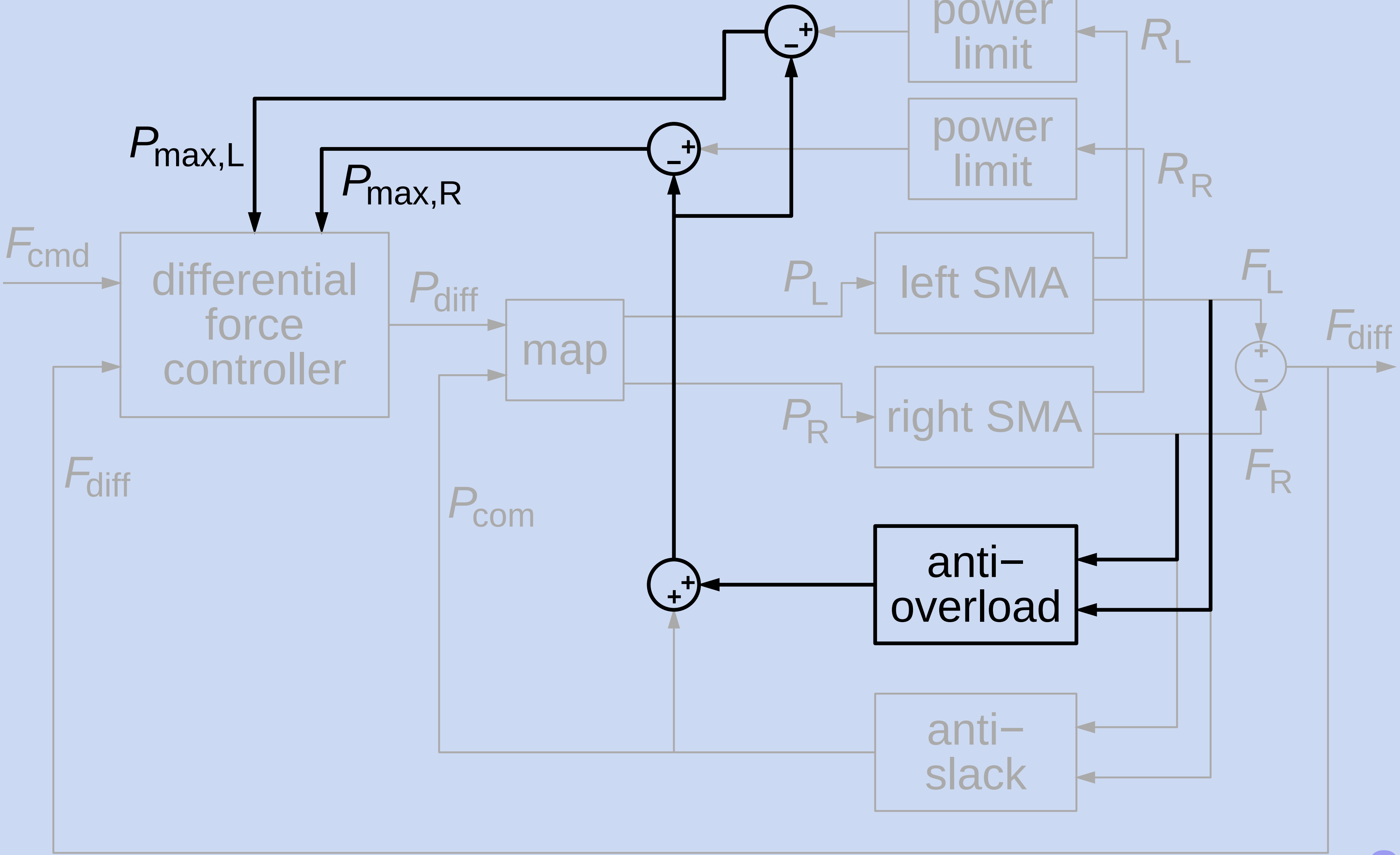



# Yet Another Problem

Rapid heating can produce excessively high tensions on the wires, which can cause damage.

remedy: an *anti−overload mechanism* that *cuts the heating power* if the tension goes too high.

# Anti−Overload Mechanism



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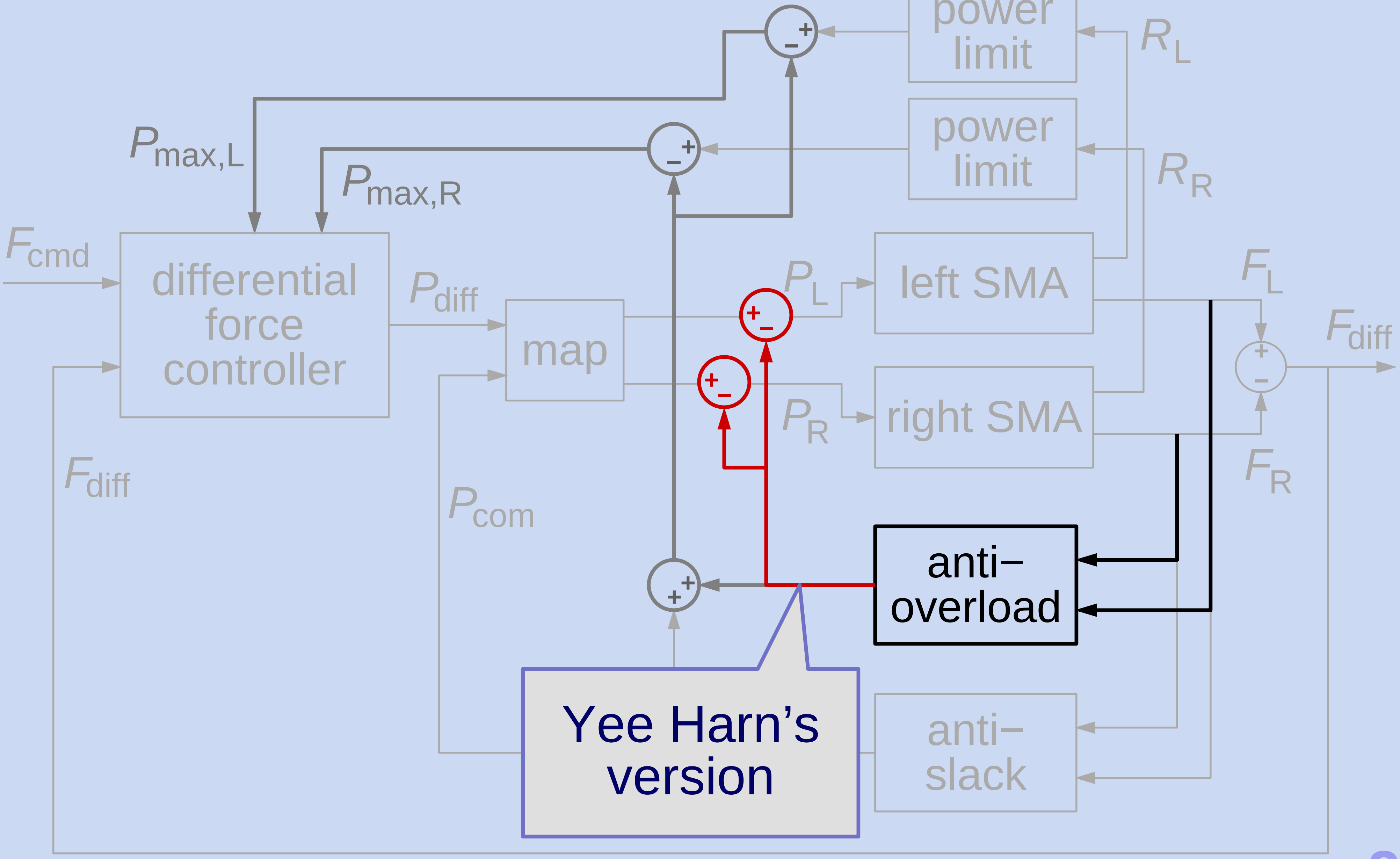

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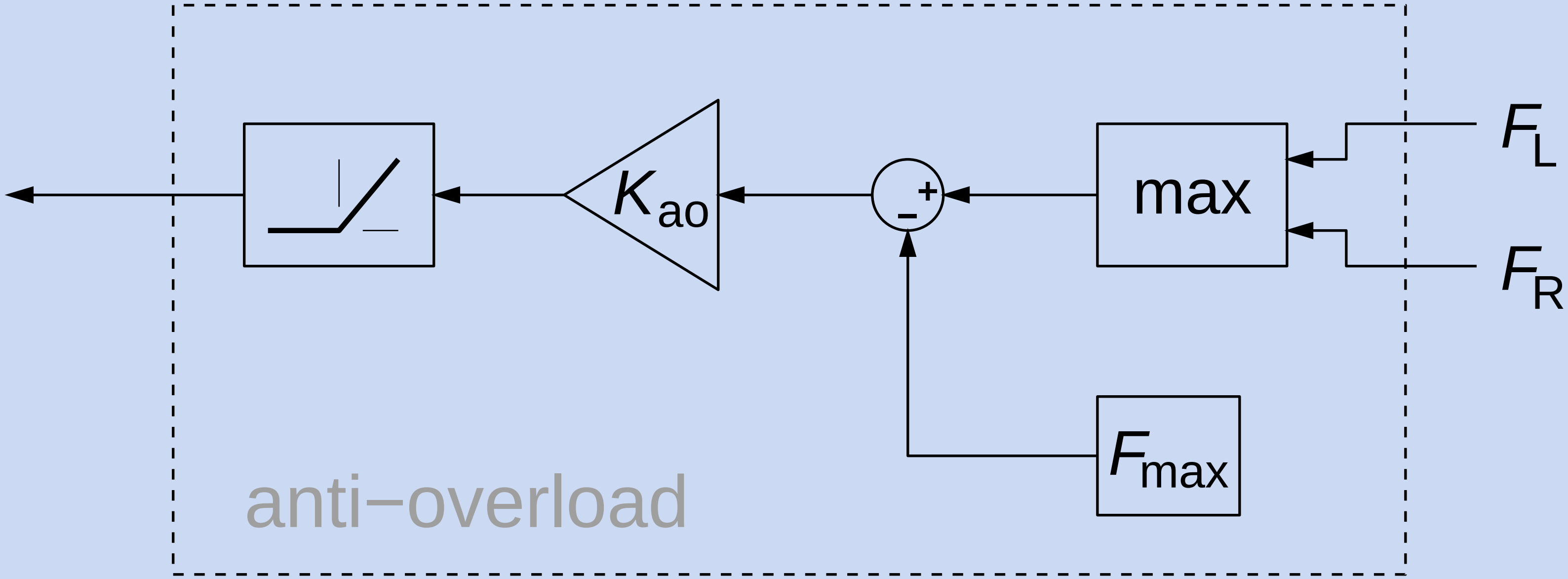
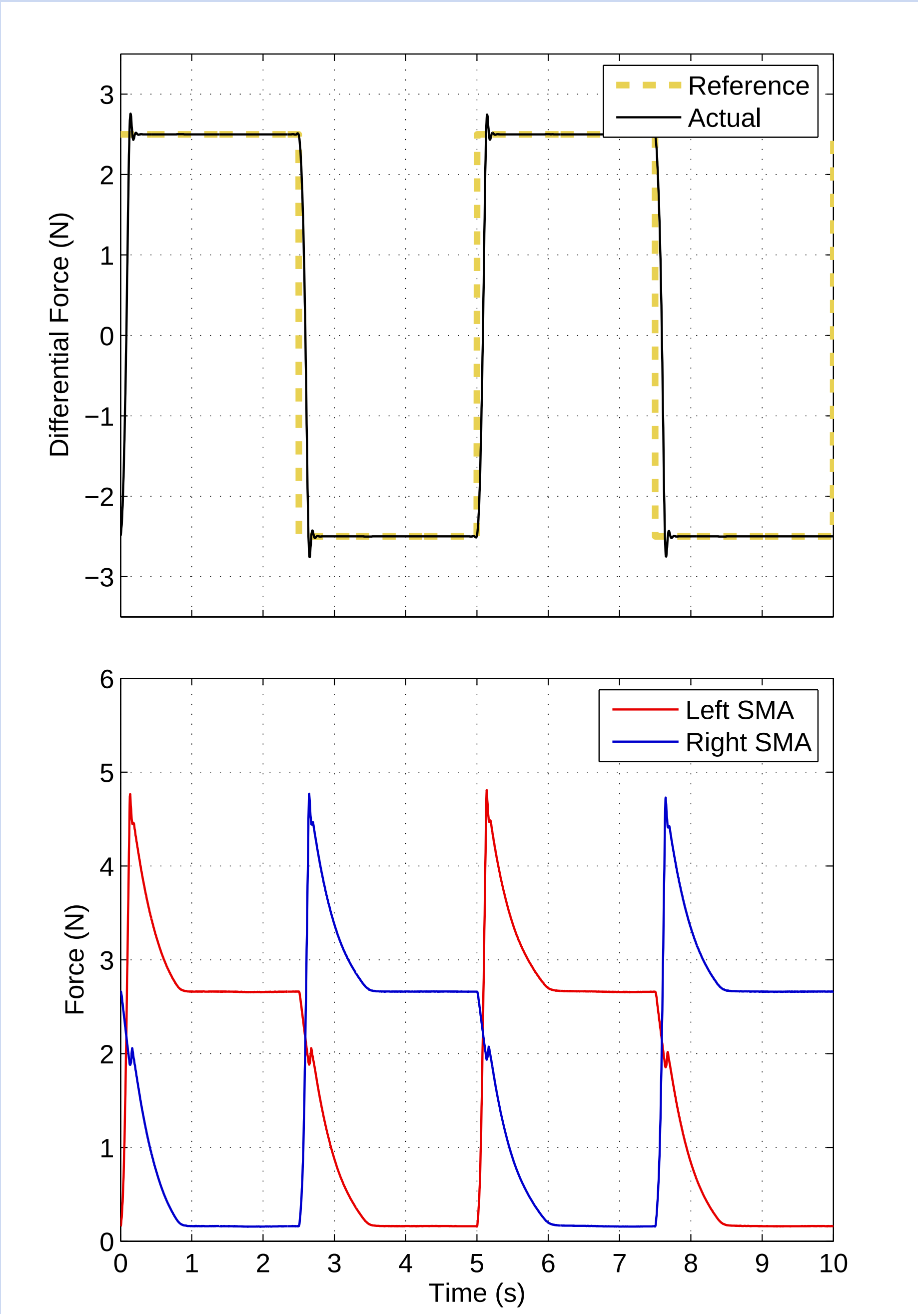
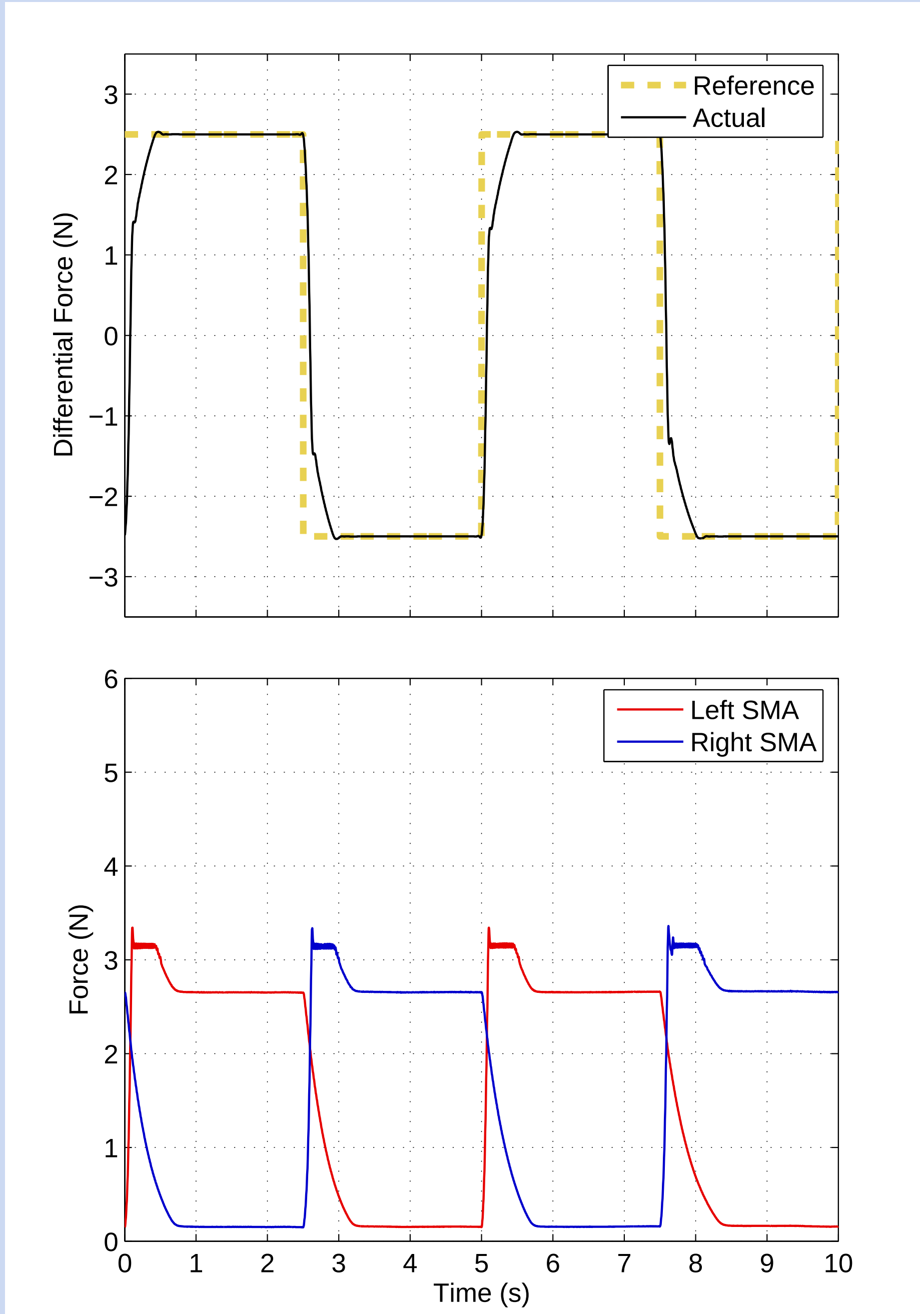


# without anti−overload




# with anti−overload



# Extension to Position and Stiffness Control

## Position

method: close an outer position loop around the force controller

result:

- very high accuracy
- low speed

## Stiffness

method: redefine the error signal to be the force error in tracking the commanded stiffness

result:

- very high accuracy
- high speed

Recommendation: Use Stiffness Control

# Summary

A new architecture for high−performance control of SMA actuators has been presented, comprising

- a PID controller for accurate control of the actuator’s output force (i.e., the differential force);
- an anti−slack mechanism to enforce a minimum tension on both wires;
- a rapid−heating mechanism that allows faster heating rates, but protects the wires from overheating; and
- an anti−overload mechanism that protects the wires from mechanical overload.

## Lessons

1. High performance can be achieved by studying the behaviour of the plant, discovering how to push the plant safely towards its performance envelope, and designing a control architecture accordingly

2. In general, such an architecture has 3 components:

   - a command−following component,
   - a performance−optimization component, and
   - a performance−limiting component with explicit knowledge of the plant's performance envelope

Acknowledgements:

- Most of the work reported here was done by Yee Harn Teh
- The experimental results graphs appearing in this talk are taken from Yee Harn's Ph.D. thesis.
- The stiffness controller (which has not been published) was implemented by Sylvain Toru

For more details, see

- Yee Harn's Ph.D. thesis
- Y. H. Teh & R. Featherstone, "An Architecture for Fast and Accurate Control of Shape Memory Alloy Actuators", *Int. J. Robotics Research*, 27(5):595−611, 2008.
- http://users.cecs.anu.edu.au/~roy/SMA/