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

Roy Featherstone
(reporting the work of Yee Harn Teh)

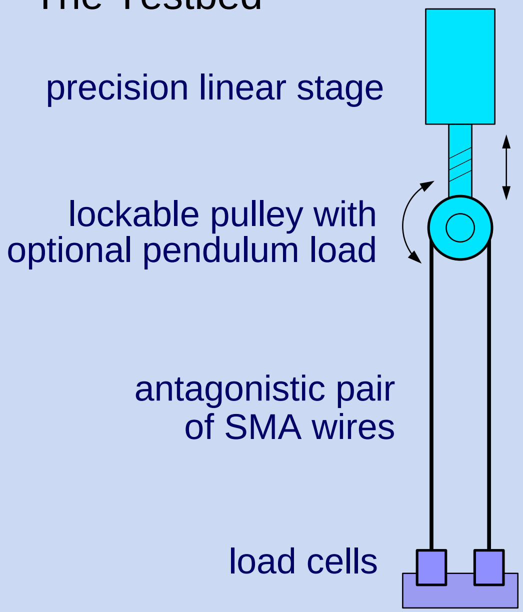
School of Engineering,
The Australian National University

this talk was presented at the
*IEEE ICRA workshop on Biologically−Inspired Actuation*,
Shanghai, Friday May 13, 2011

© 2011 Roy Featherstone
© 2006 R. Featherstone, Y. H. Teh

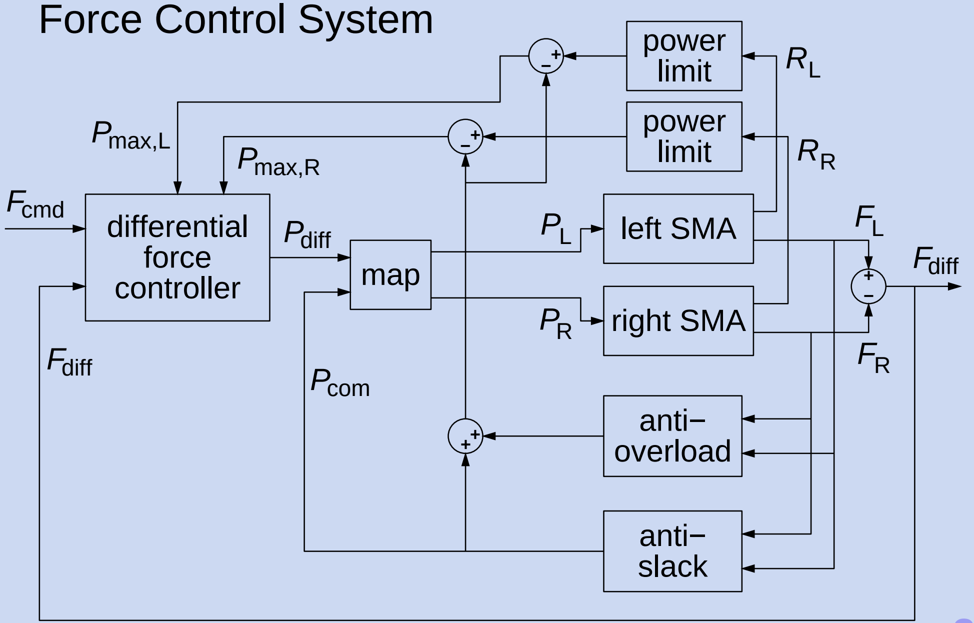


## The Testbed



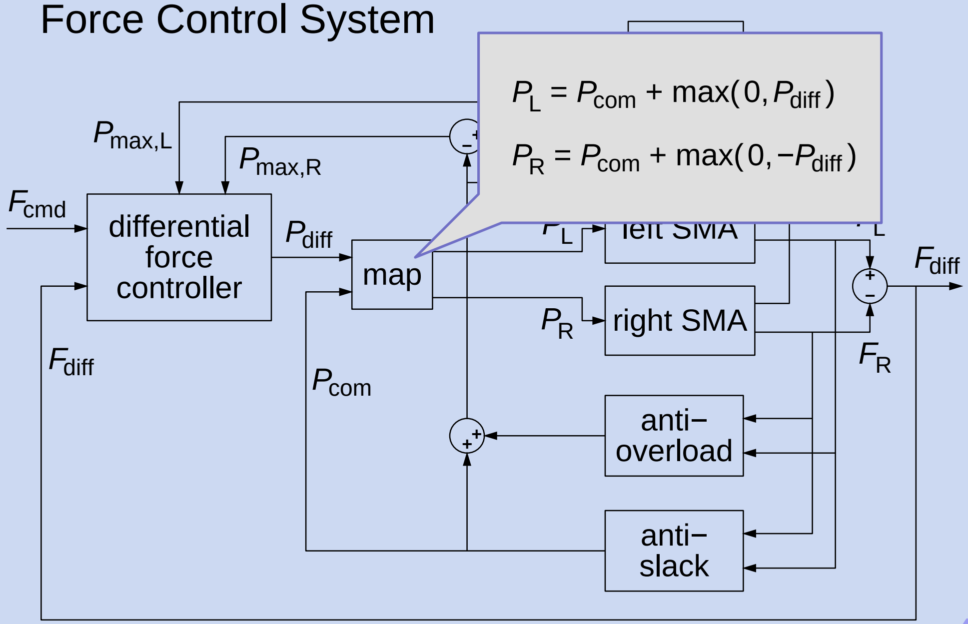



## Force Control System

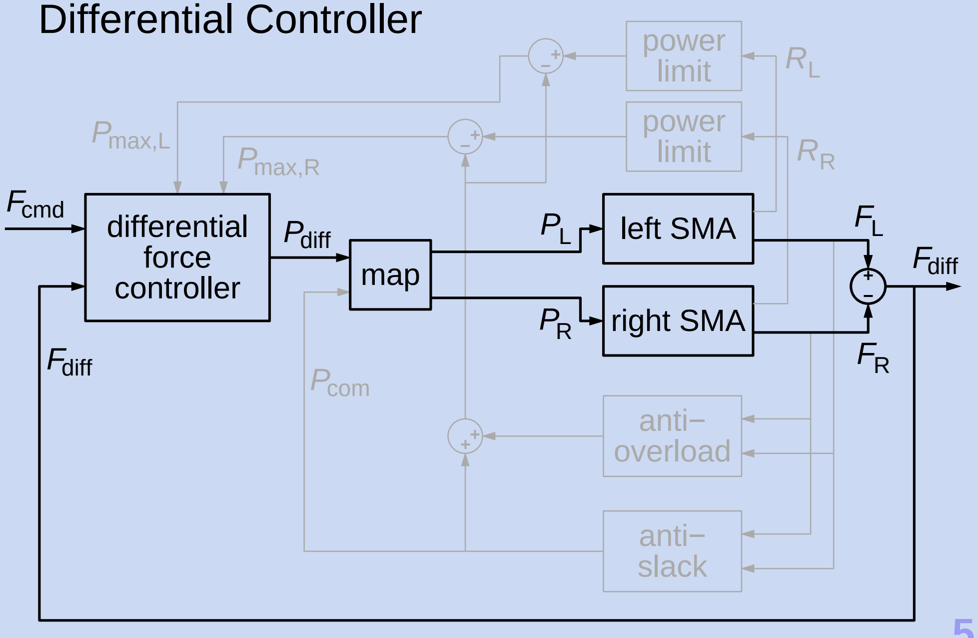





## Force Control System

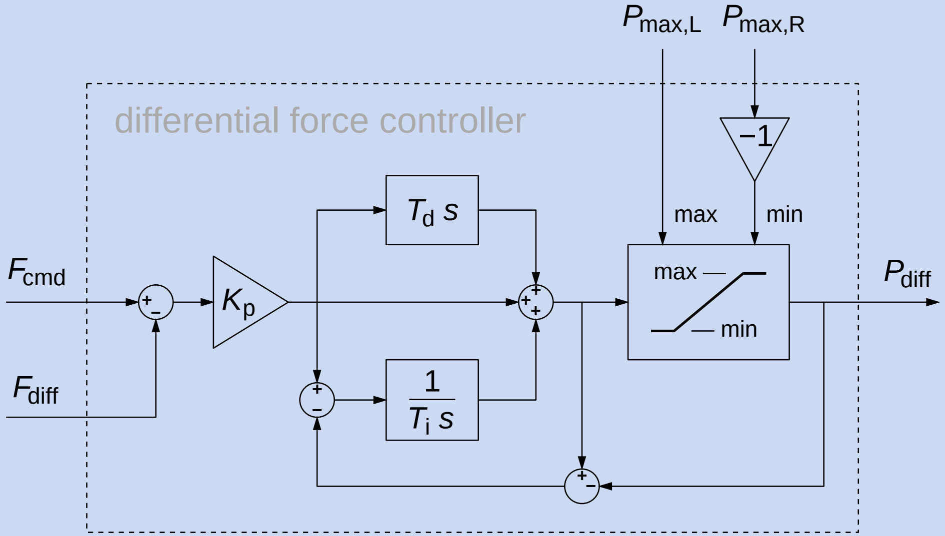


## Differential Controller




5

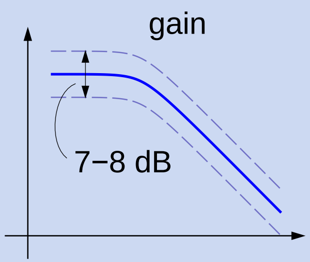
## Differential Controller



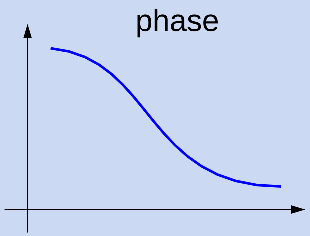

6

## Behaviour of the Plant

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

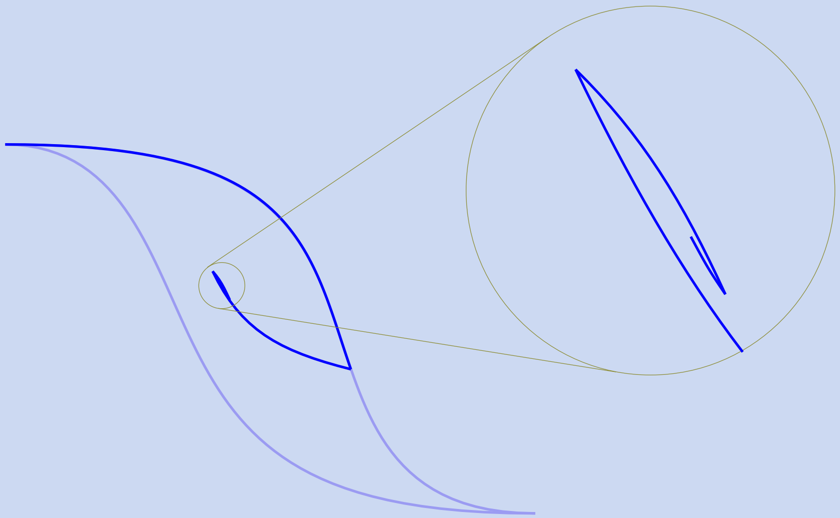



- Gain varies with mean stress and strain in a 7−8 dB range
- Phase is *independent of stress and strain*
- Cut−off frequency varies with wire diameter




7

## What Happened to the Hysteresis?



8

# A Problem

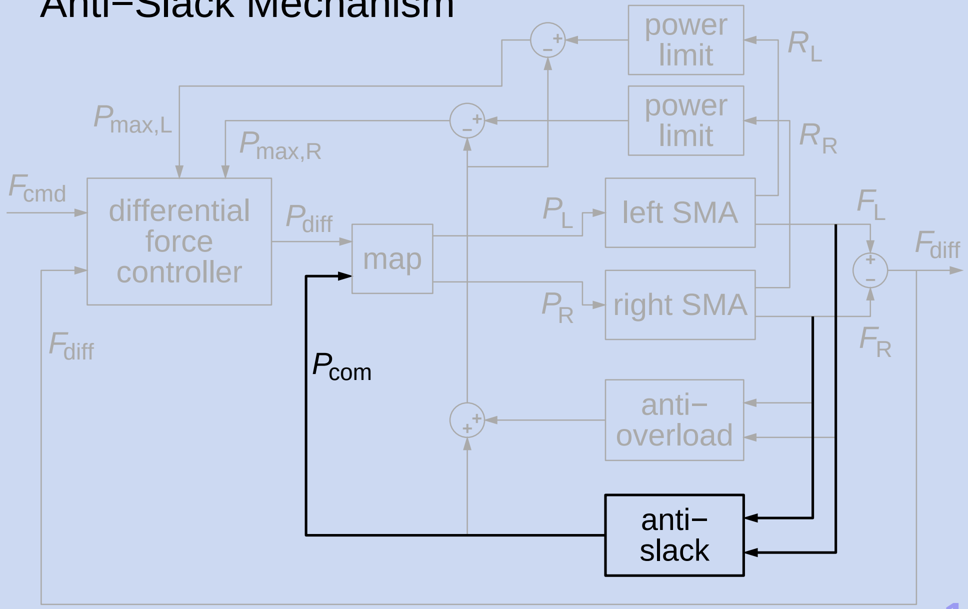
When Flexinol™ wires are used in an antagonistic−pair actuator, they quickly develop a *two−way shape memory effect*, in which the wires *actively lengthen* as they cool, even if the tension on the wire is zero.

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.

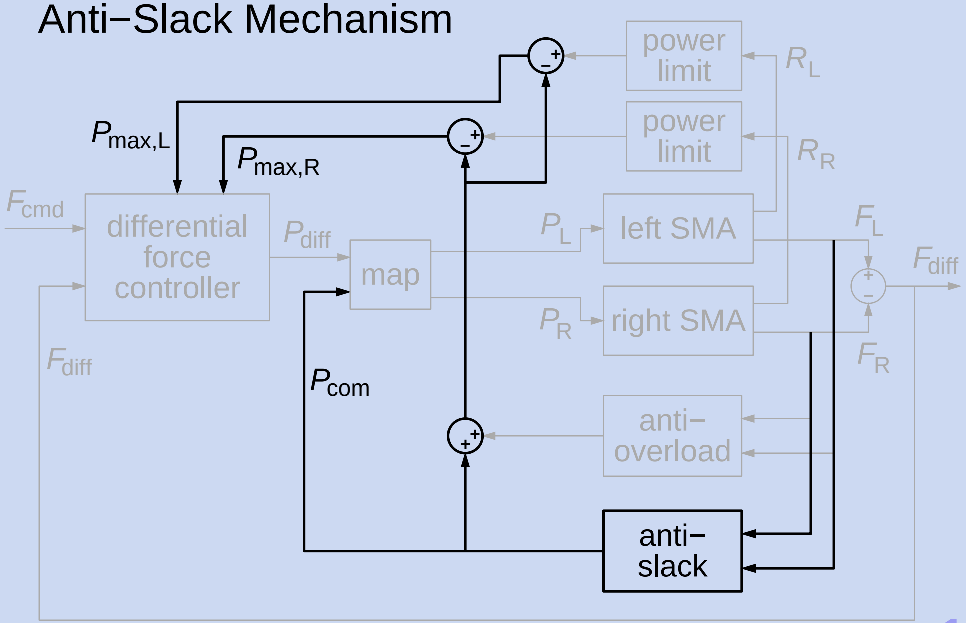


# Anti−Slack Mechanism



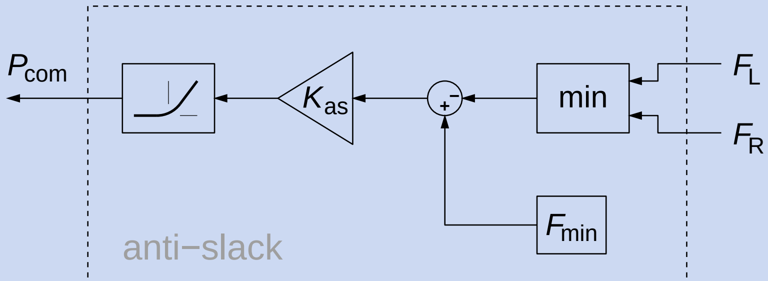



# Anti−Slack Mechanism

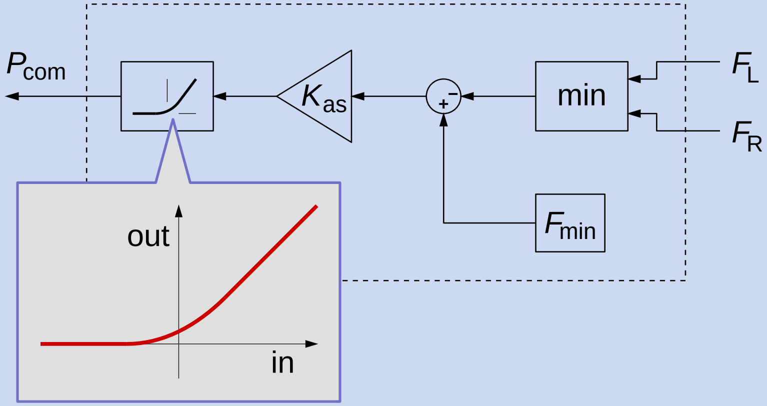




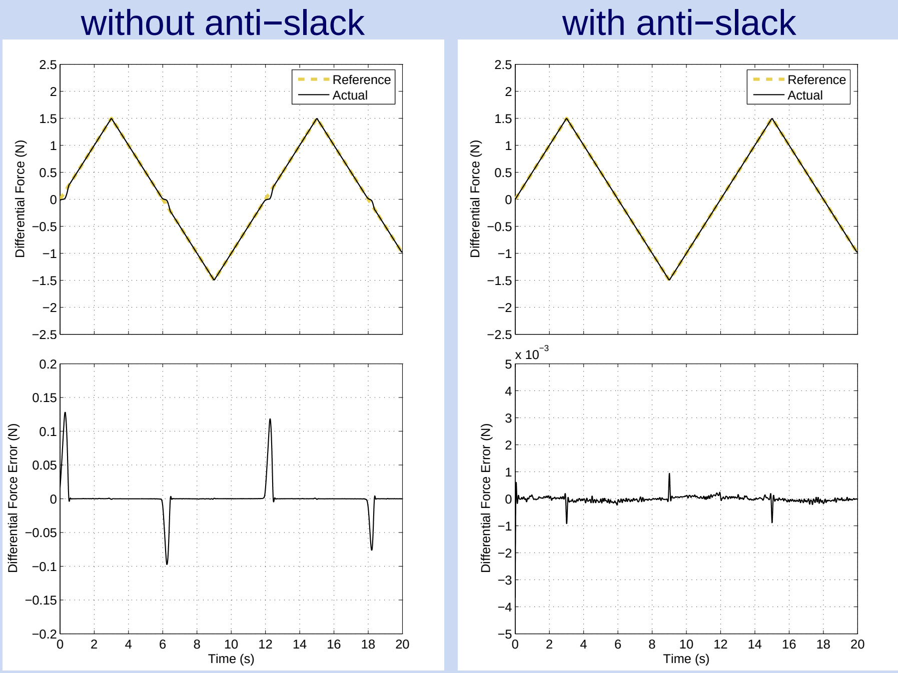

# Anti−Slack Mechanism



# Anti−Slack Mechanism








# 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™ 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.

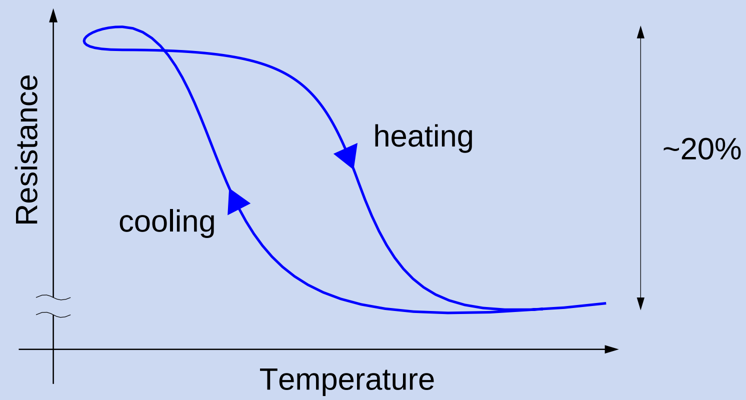
This can be accomplished by

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



## Electrical Resistance vs. Temperature

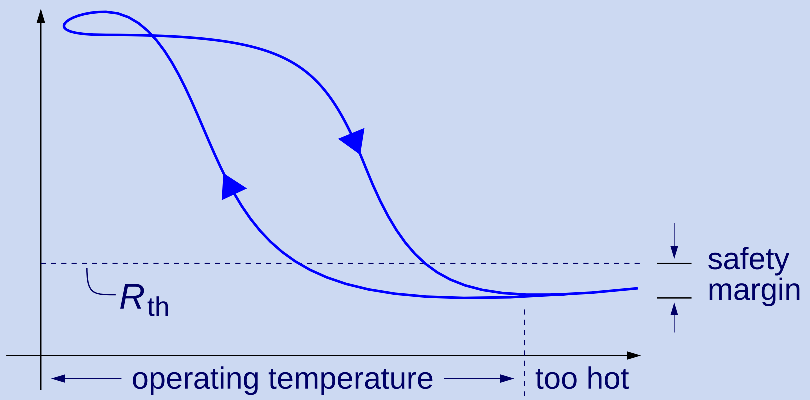
The electrical resistance (of nitinol) varies with the martensite ratio, and therefore also with temperature, because the resistivity of the martensite phase is about 20% higher than the resistivity of the austenite phase.






## Calculating the Power Limit

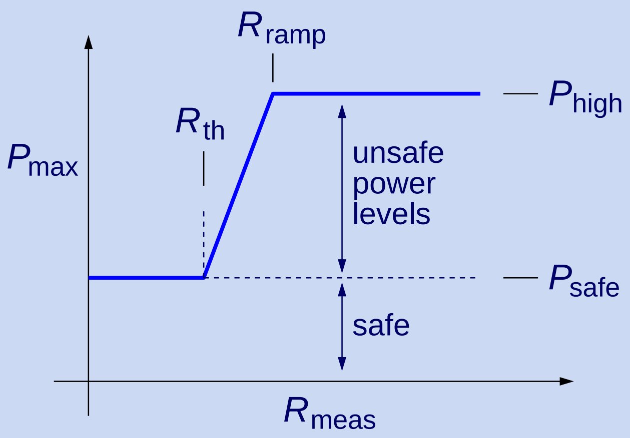
1. Choose a threshold resistance, $R_{th}$, which is equal to the hot resistance of the wire plus a safety margin.



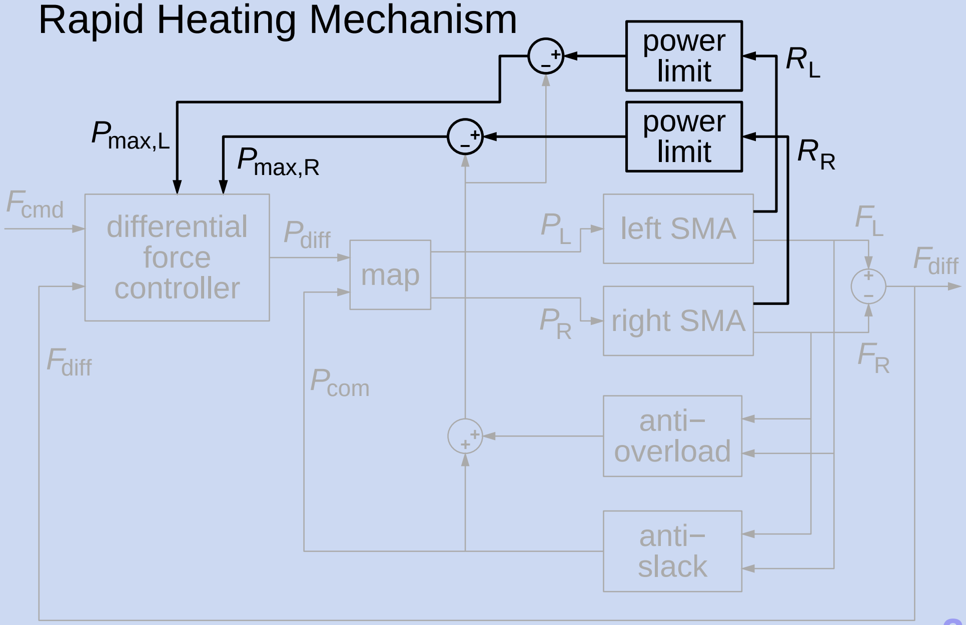



## Calculating the Power Limit

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



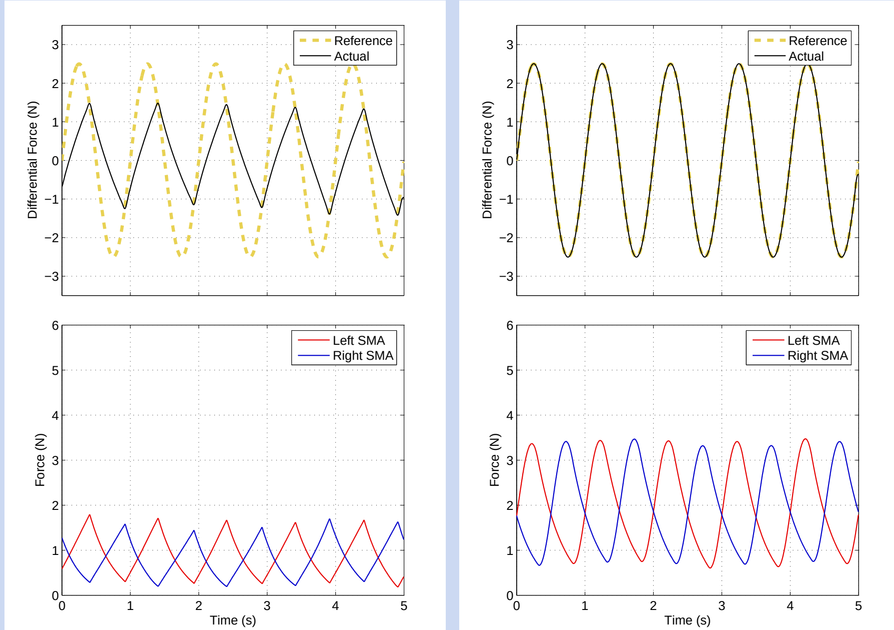
## Rapid Heating Mechanism






without rapid heating

with rapid heating





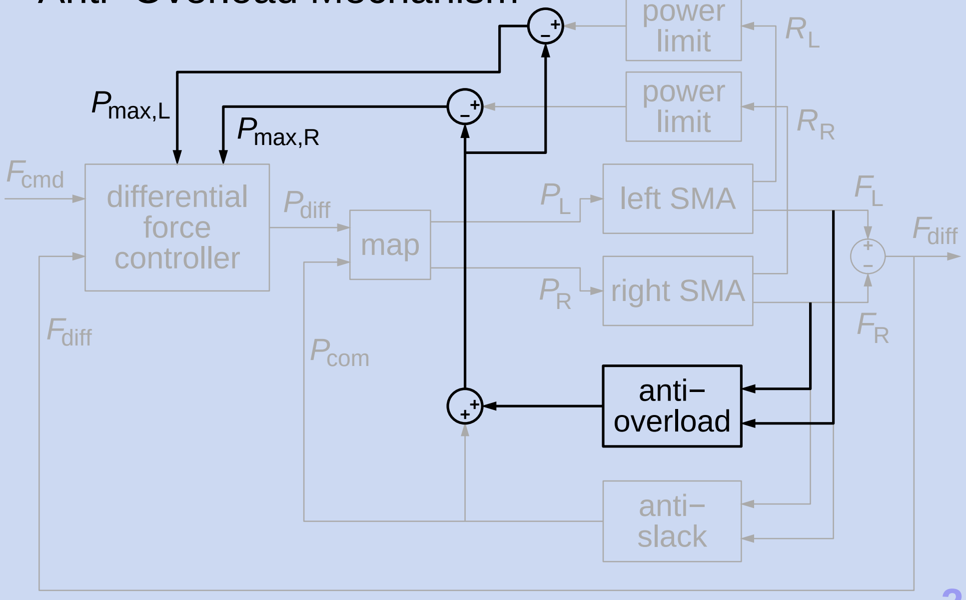

## Yet Another Problem

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

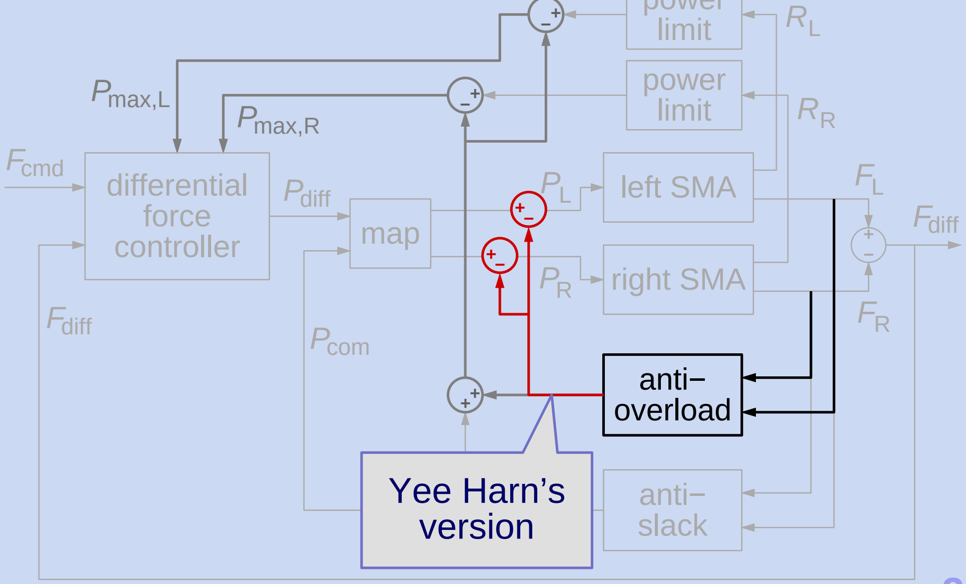
remedy: an *anti−overload mechanism* that *cuts the heating power* if the tension goes too high.



## Anti−Overload Mechanism

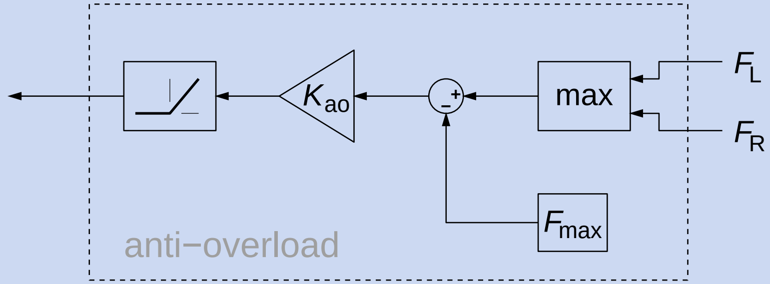


## Anti−Overload Mechanism



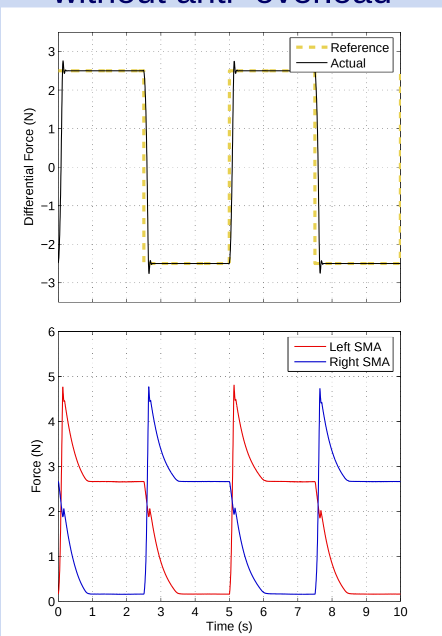



## Anti−Overload Mechanism

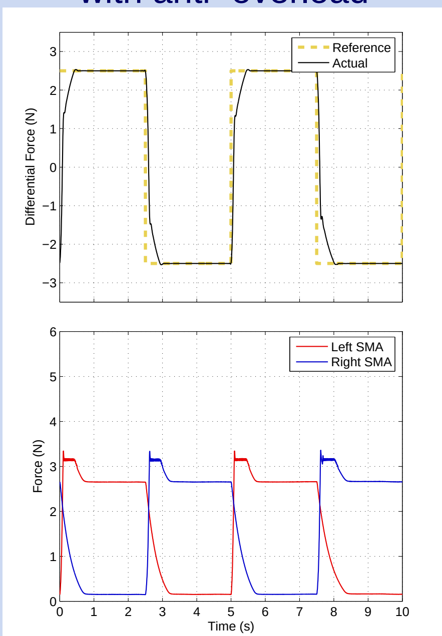





### without anti−overload




### 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/