Balancing Made Simple

by Roy Featherstone

presented at the IROS 2018 Workshop on

Modelling and Control of Dynamic Legged Locomotion: Insights from Template (Simplified) Models

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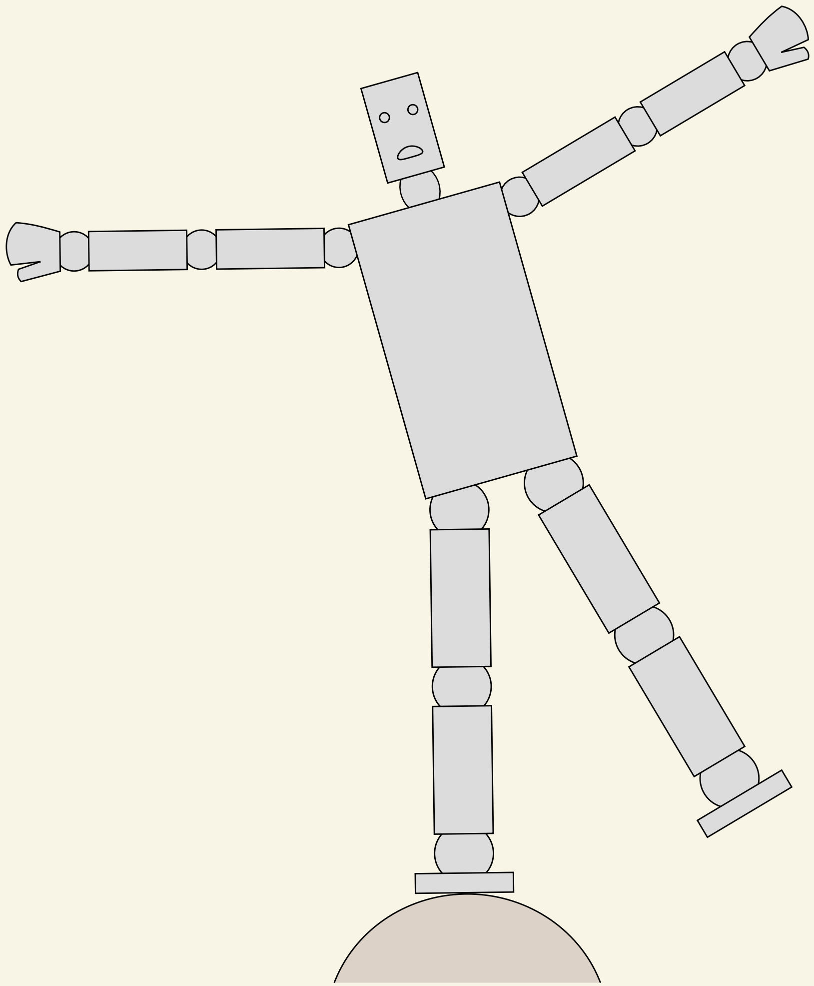
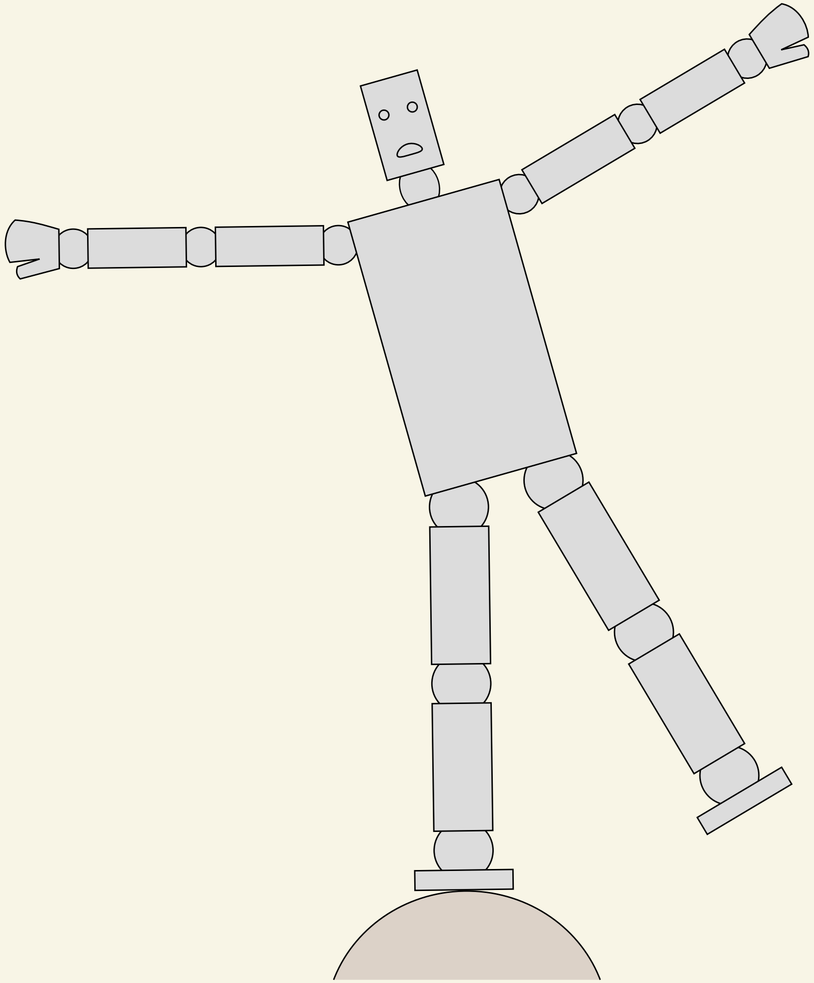
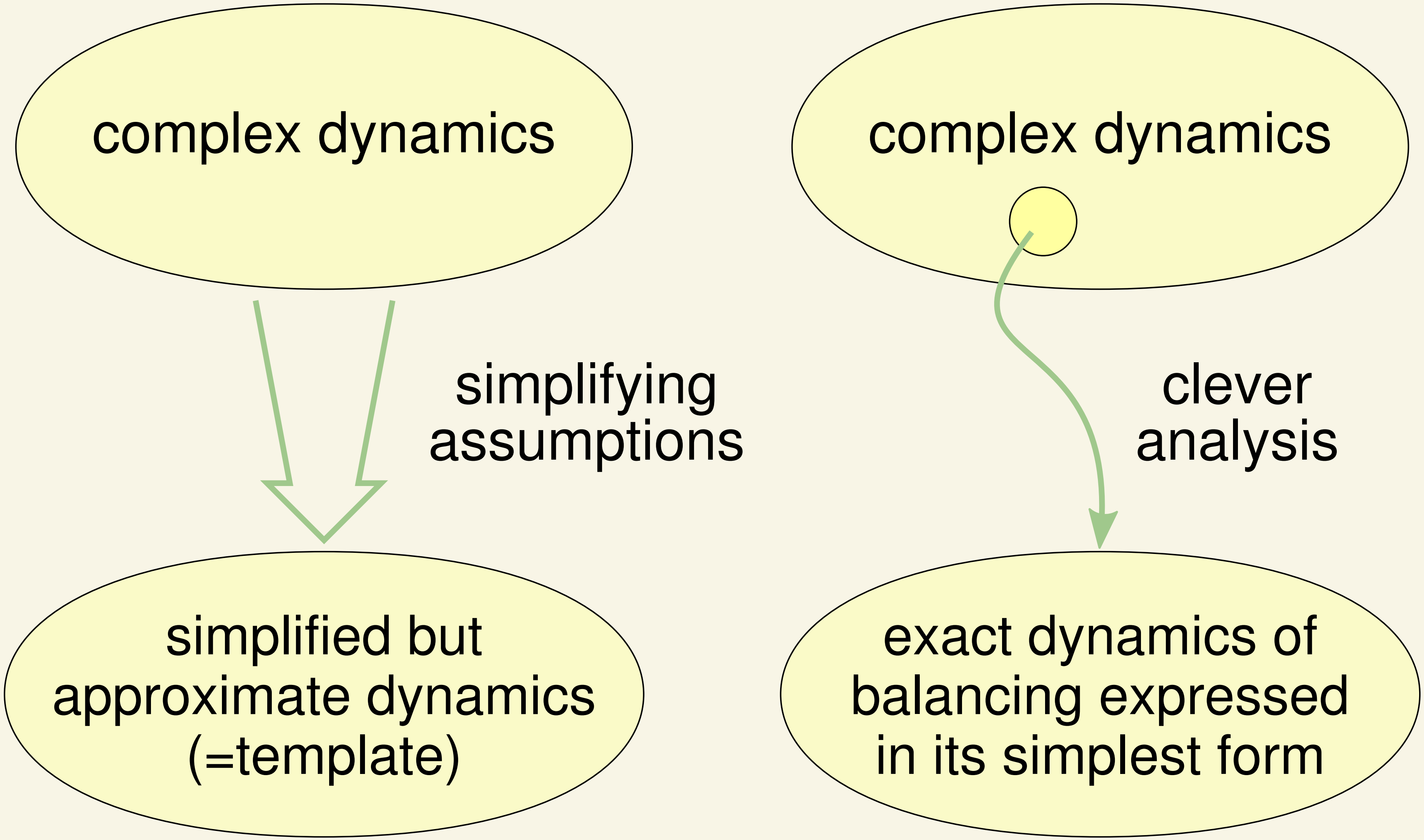


The topic of this talk is how to balance on a single point (not a polygon) of support



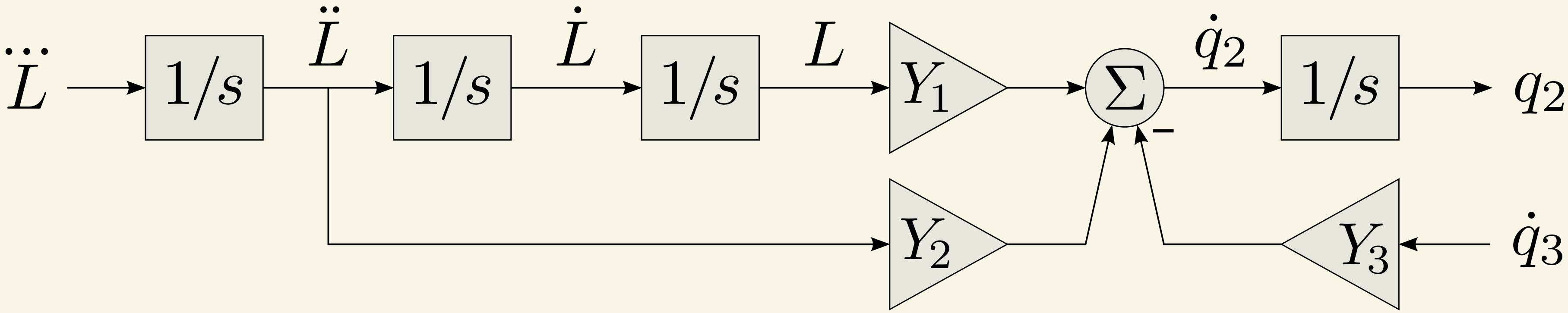
The topic of this talk is how to balance on a single point (not a polygon) of support...

and perform large, fast movements at the same time.



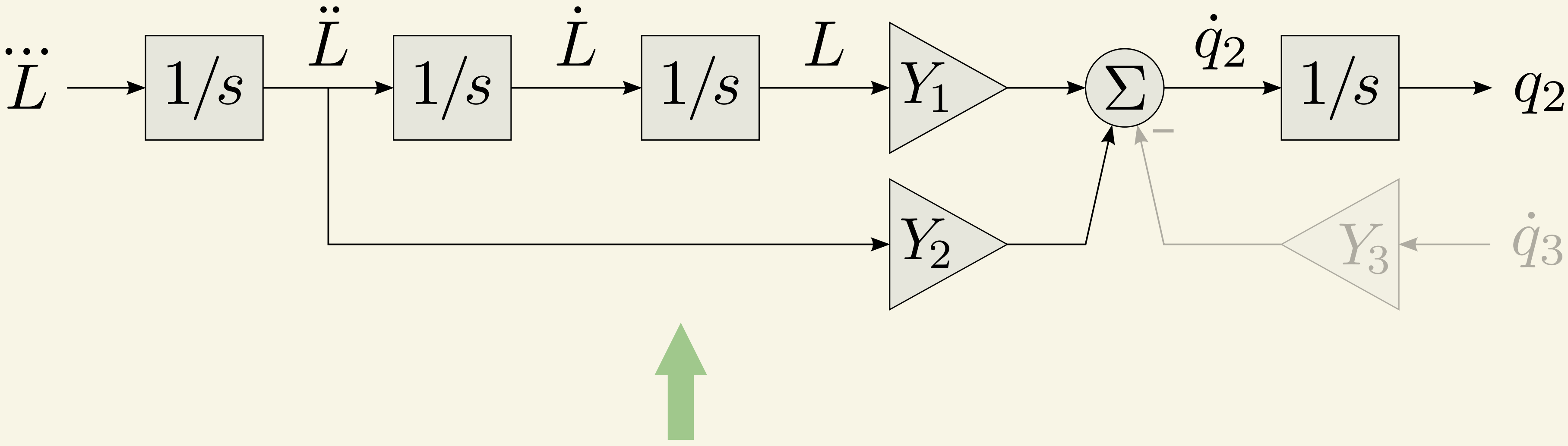
templates are not the only way to achieve simplicity

The Simple Dynamics of Balancing



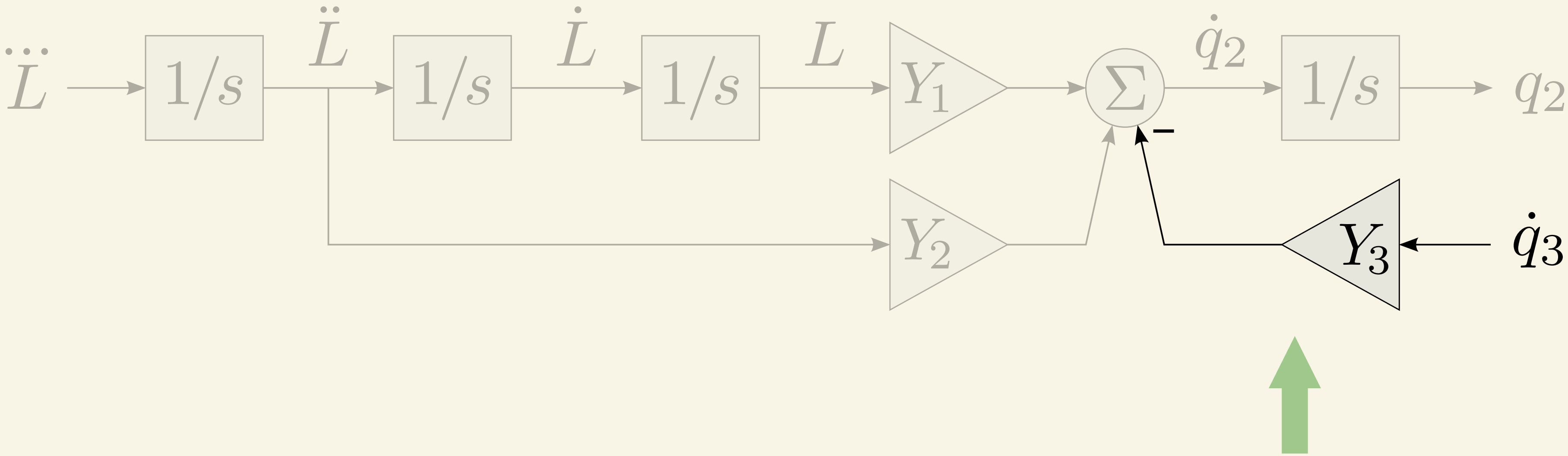
The physical process of balancing can be expressed in the form of this block diagram, which serves as the *plant* for the balance controller to control.

The Simple Dynamics of Balancing



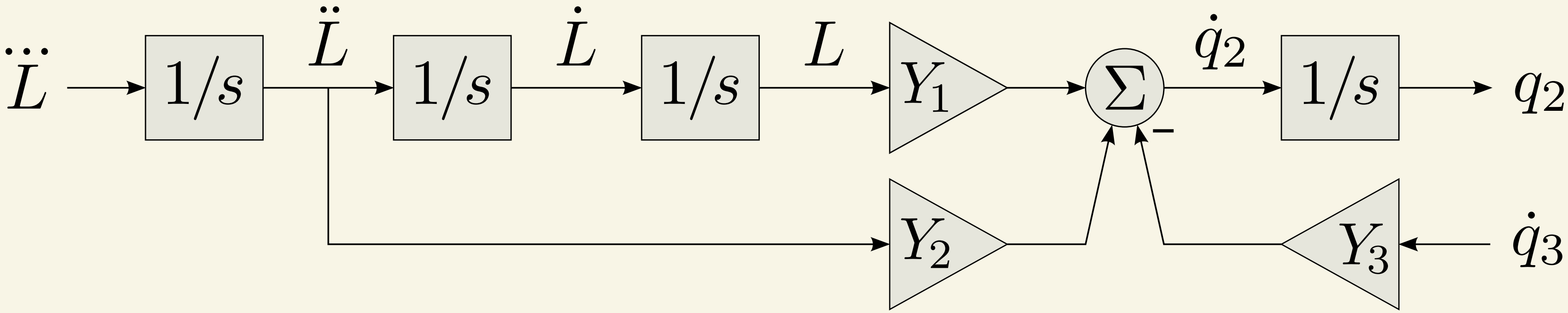
This portion is concerned with balancing

The Simple Dynamics of Balancing



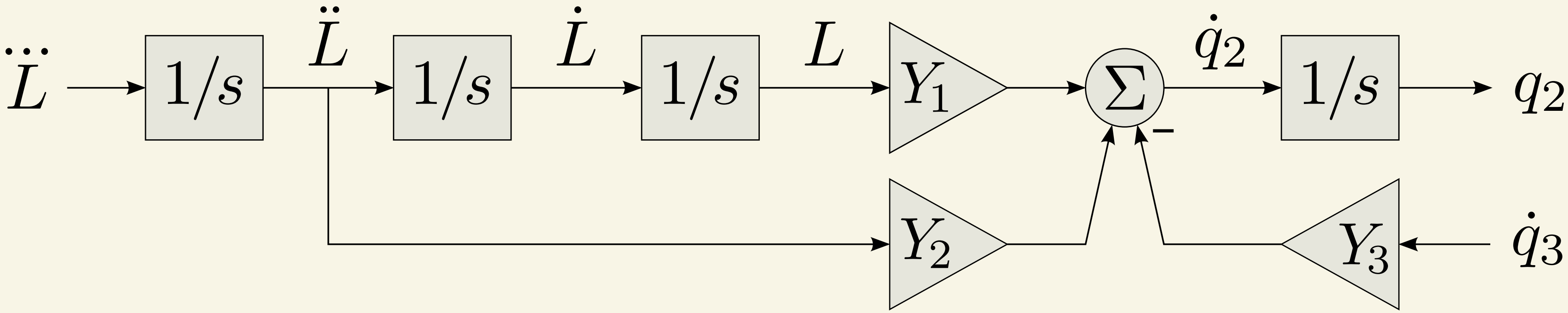
and this portion describes the disturbances caused by other motions.

The Simple Dynamics of Balancing



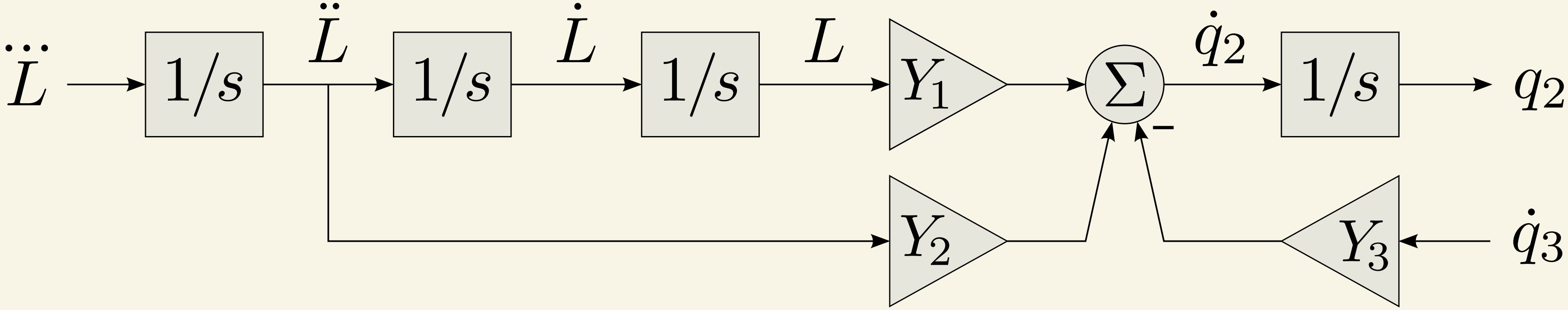
- L angular momentum of the robot about the support
- q_1 variable(s) describing the robot's motion relative to the ground
- q_2 *overloaded* variable(s) used *both* to balance *and* to follow motion commands
- q_3 all other robot variables

The Simple Dynamics of Balancing



The balancing behaviour of the robot depends only on the two gains Y_1 and Y_2 which are easily calculated functions of the robot's configuration variables.

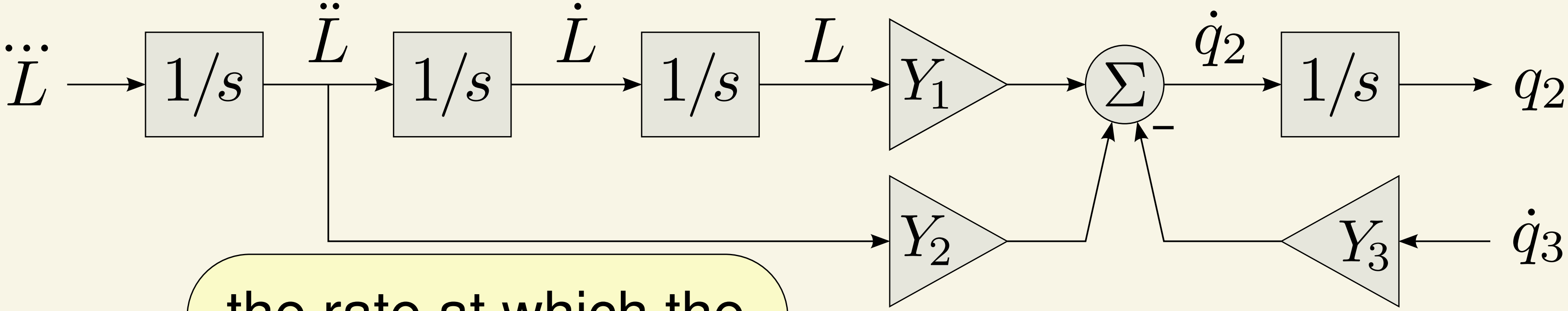
The Simple Dynamics of Balancing



Y_1 and Y_2 are functions of two easily measured physical properties of the robot:

- the natural time constant of toppling, and
- the linear velocity gain of $\dot{q}_2$

The Simple Dynamics of Balancing



the rate at which the robot begins to fall, treating it as a single rigid body

Y_1 and … wo easily measured physical propert…

- the natural time constant of toppling, and
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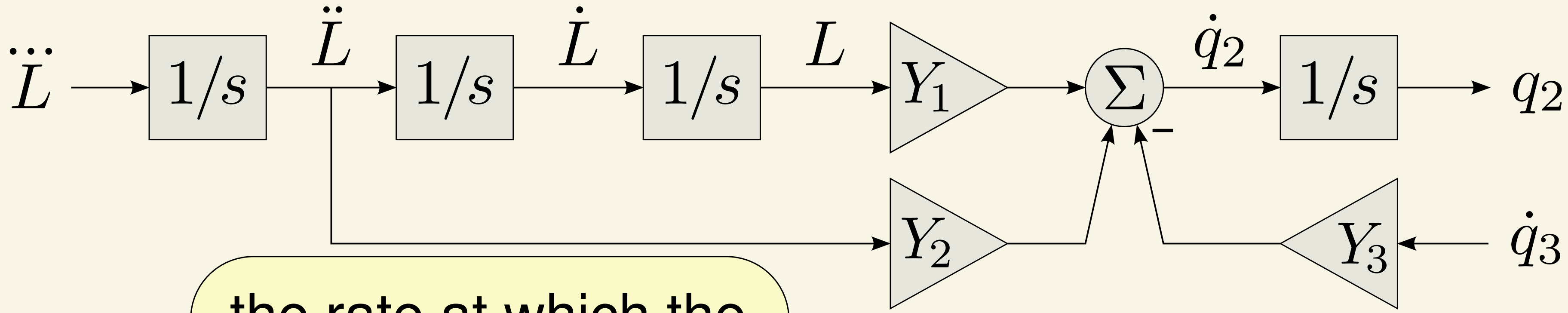
The Simple Dynamics of Balancing



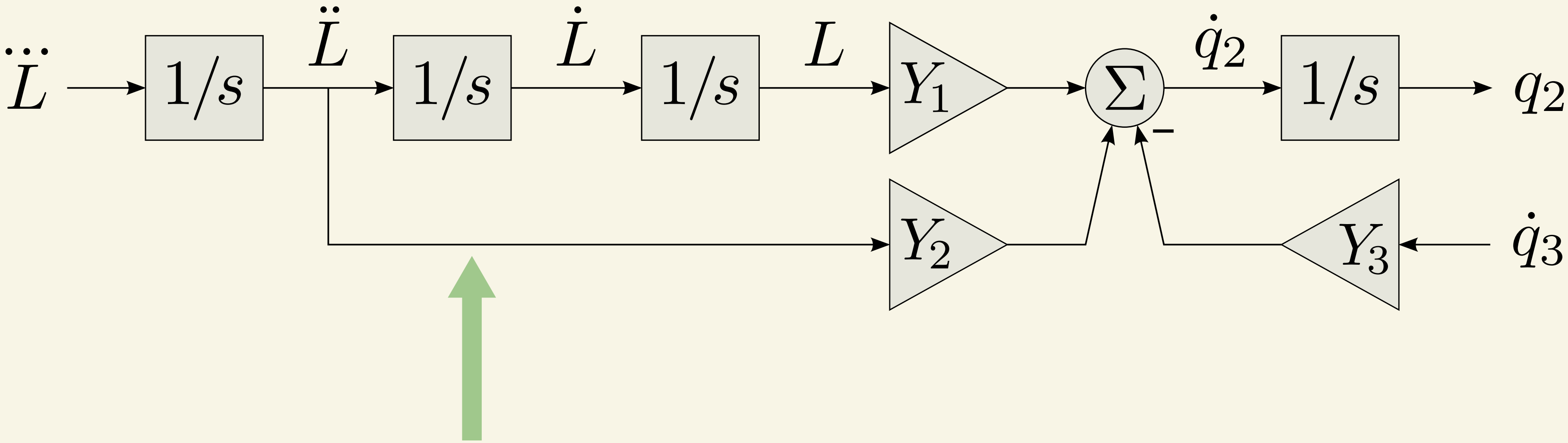
the rate at which the robot begins to fall, treating it as a single rigid body

Y_1 and … wo easily measured physical propert…

- the natural time constant of toppling, and
- the linear velocity gain of $\dot{q}_2$

the step change in CoM velocity caused by a unit step change in $\dot{q}_2$

The Simple Dynamics of Balancing



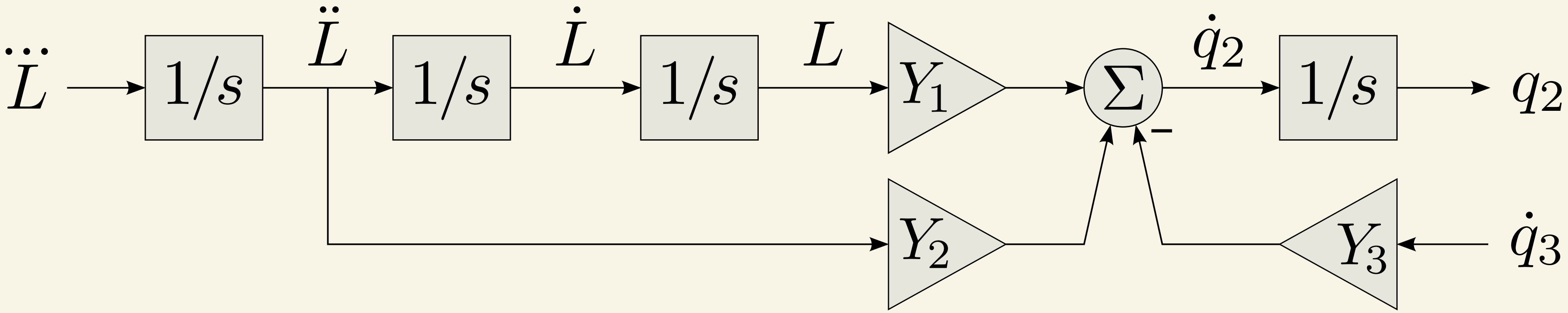
In 2D, these signals are all scalars.
In 3D, they are 2D vectors.

High-Performance Balance Control

A robot has high-performance balance control if it can do the following:

- accurately follow commands to make large, fast movements without losing its balance; and
- quickly recover from large balance disturbances

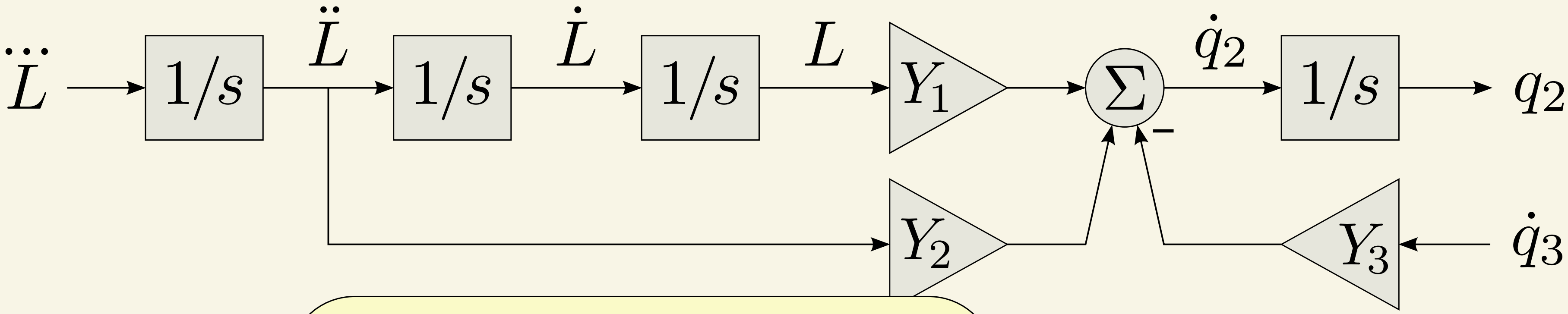
Simple Balance Control



High-performance balancing can be achieved using

- a simple control law closed around *this plant*
- and a simple *acausal filter* that implements *leaning in anticipation* of the balance disturbances that will be caused by commanded future motions.

Simple Balance Control



a first-order low-pass filter running *backwards* in time from the future to the present

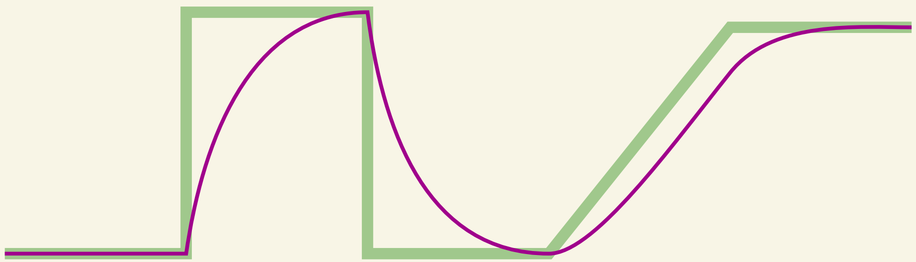
High-perfor … achieved using

- a simple … nd *this plant*
- and a simple *acausal filter* that implements *leaning in anticipation* of the balance disturbances that will be caused by commanded future motions.

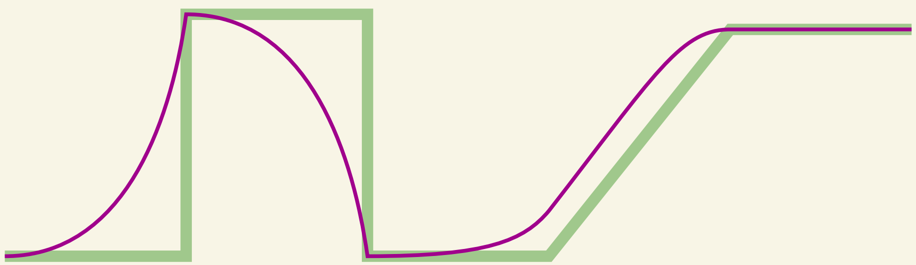
The Acausal Filter

a first-order low-pass filter running backwards in time

normal low-pass filter



acausal low-pass filter



transfer function

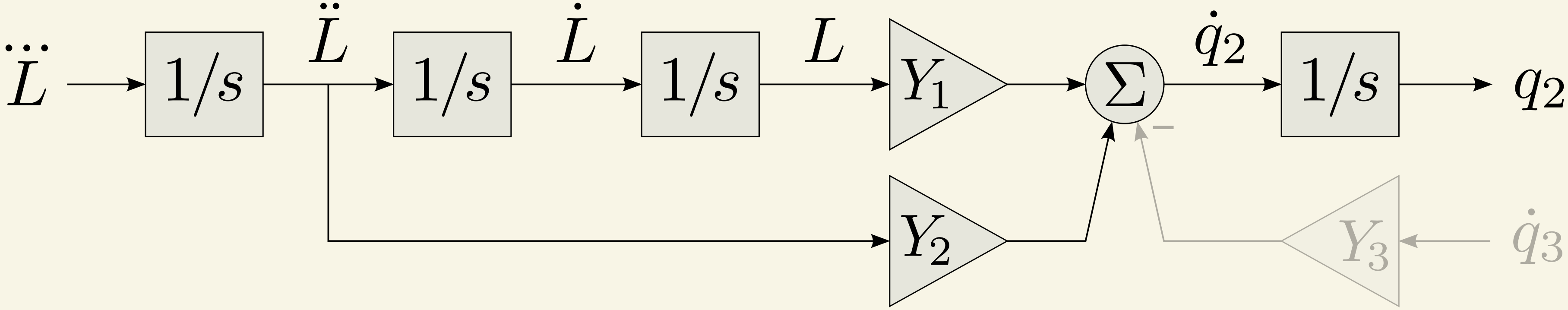
$$\frac{1}{1 + T_c s}$$

natural time constant of toppling

$$\frac{1}{1 - T_c s}$$

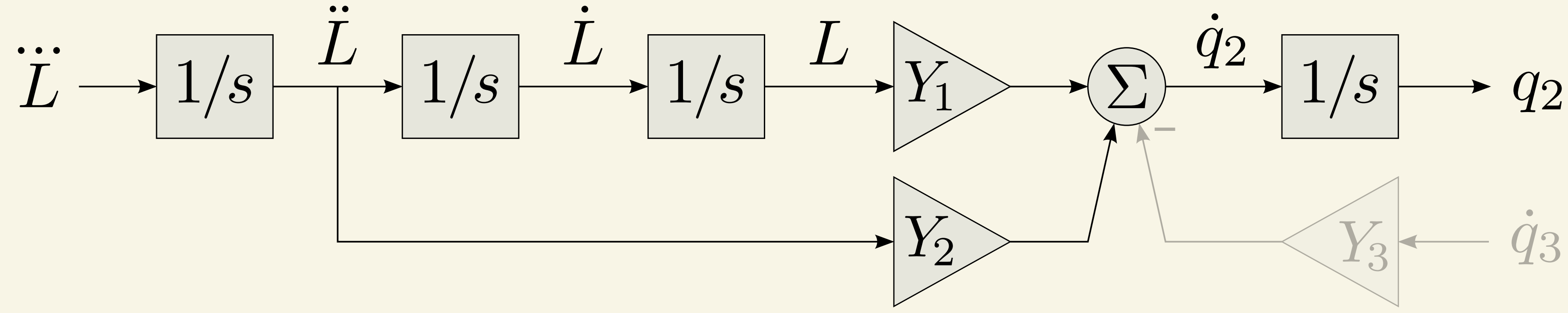
unstable pole in forward time

Balance Control Law



$$\dddot{L} = k_{dd}\ddot{L} + k_d\dot{L} + k_L L + k_q(q_2 - AF(u))$$

Balance Control Law



$$\dddot{L} = k_{dd}\ddot{L} + k_d\dot{L} + k_L L + k_q(q_2 - AF(u))$$

feedback gains

acausal filter

feedforward gains

$$u = q_{2c} + \alpha_1 \dot{q}_{2c} + \alpha_2 \ddot{q}_{2c}$$

command signal and derivatives

Experimental Results (Tippy balancing using crossbar)

actual response q_2 very closely follows theoretical response q_t

Website: http://royfeatherstone.org/skippy

Acknowledgements: the video and the experimental results were produced by the Skippy Team

THE END