

# DLS Lab annual seminar

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# Introduction

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## About me

**Master thesis: "Dynamic control  
of 3D directional drilling systems  
using state estimation"**

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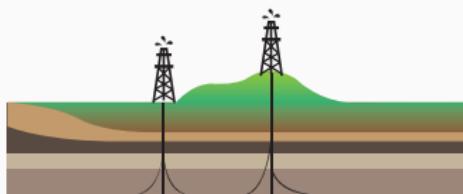
# Dynamic control of 3D directional drilling systems

- Challenging dynamic system
- Collaboration between researchers of TU Eindhoven, TU Delft and the University of Minnesota
- Little research on this field

# Applications of directional drilling

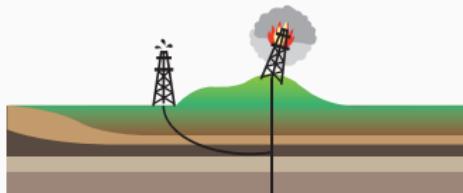


- Extract oil, mineral and thermal energy resources

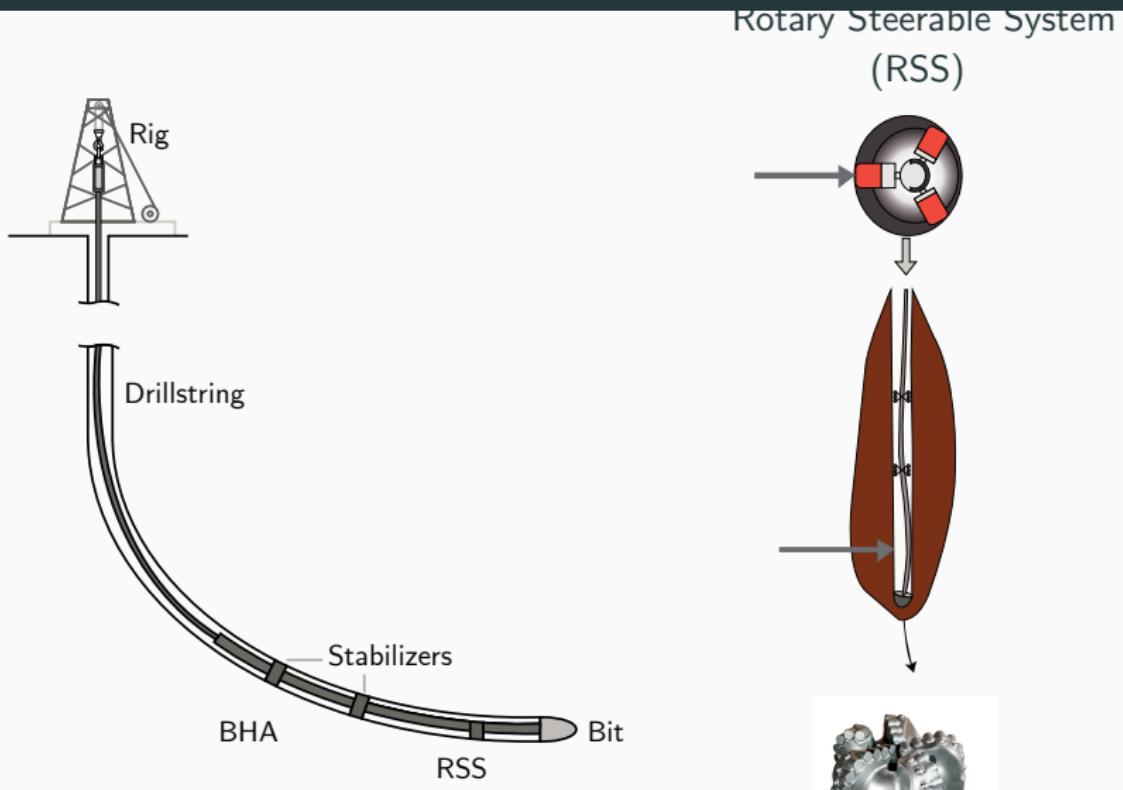


- Reach targets that need complex geometries such as:

- Under a city or an ecosystem
- Far from the drill rig
- Relief for hazardous situations



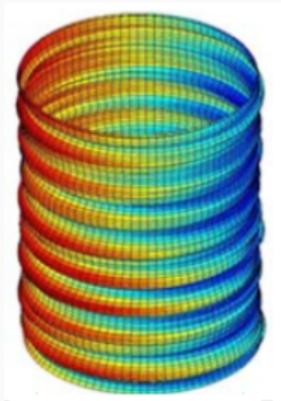
# General description of the system



BHA: Bottom hole assembly

## Context and challenges

- State-of-practice: Constant RSS force



- Negative effects: kinking, rippling and spiraling
- Consequences of negative effects: reduced penetration rate and accuracy

[Sugiura 2009]

# Research goals

## Main goal

Develop a control strategy for a 3D directional drilling system, that allows to drill boreholes with complex geometries.

## Previous works

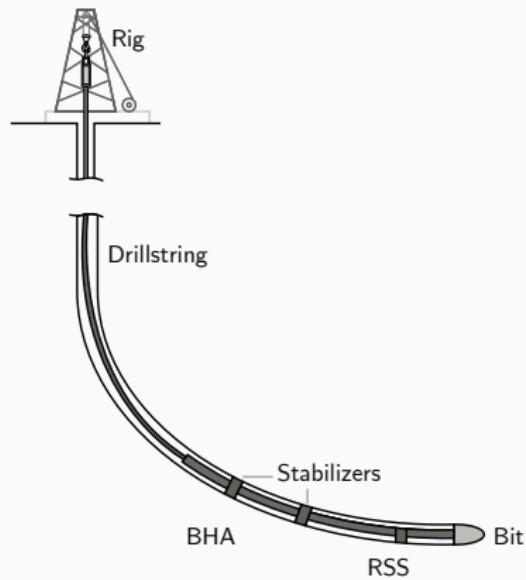
- Model of 3D directional drilling systems [Perneder 2013]
- Model-based decoupled control of a 3D directional drilling system [Monsieurs 2015]
  - State-feedback controller
  - Relies on availability of measurements of the states (not possible in practice)

## Subgoals

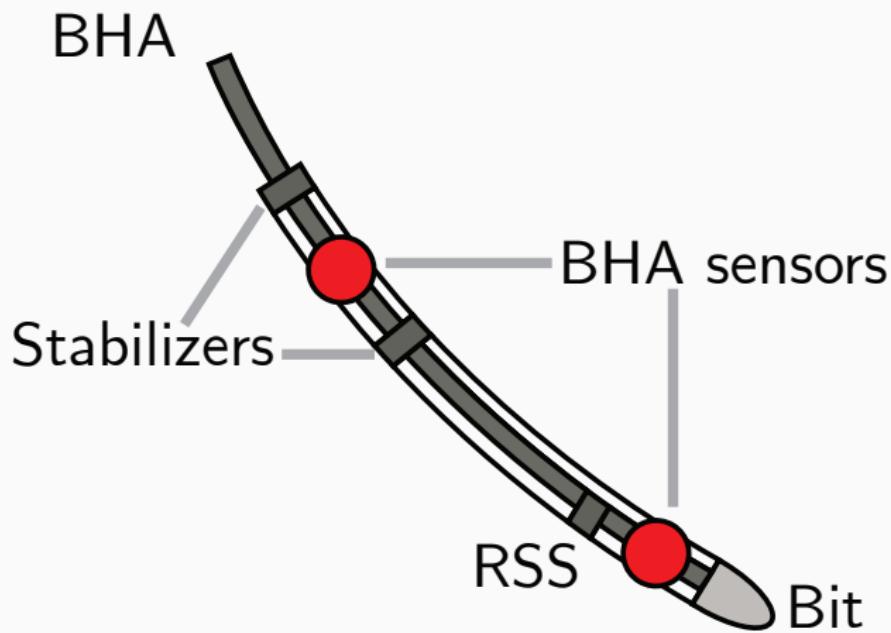
- Control strategy that relies only on local measurements
- Robustness against parametric uncertainty

# Model characteristics

- Function of (dimensionless) borehole length  $\xi$
- Model form: nonlinear coupled delay differential equations (delays: BHA should fit in already drilled borehole)
- States: borehole inclination ( $\Theta$ ) and azimuth ( $\Phi$ ) at the bit
- No access to measurements of the states (output equations of sensors)



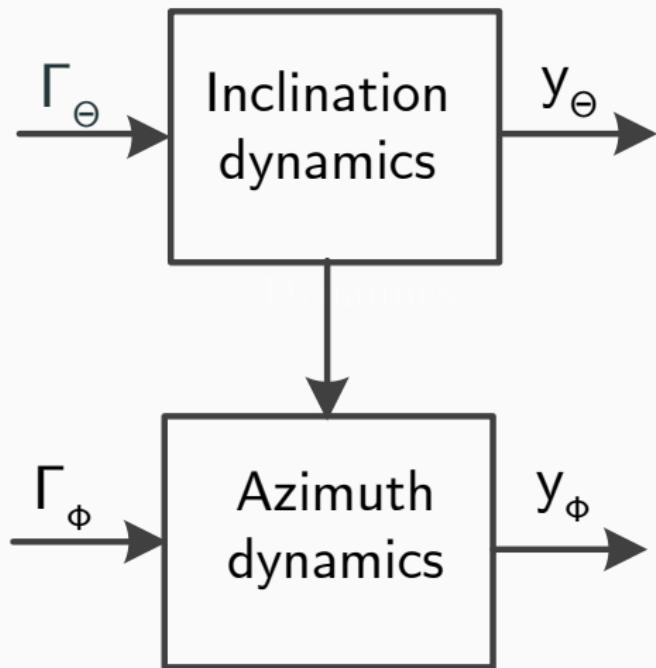
## Available measurements



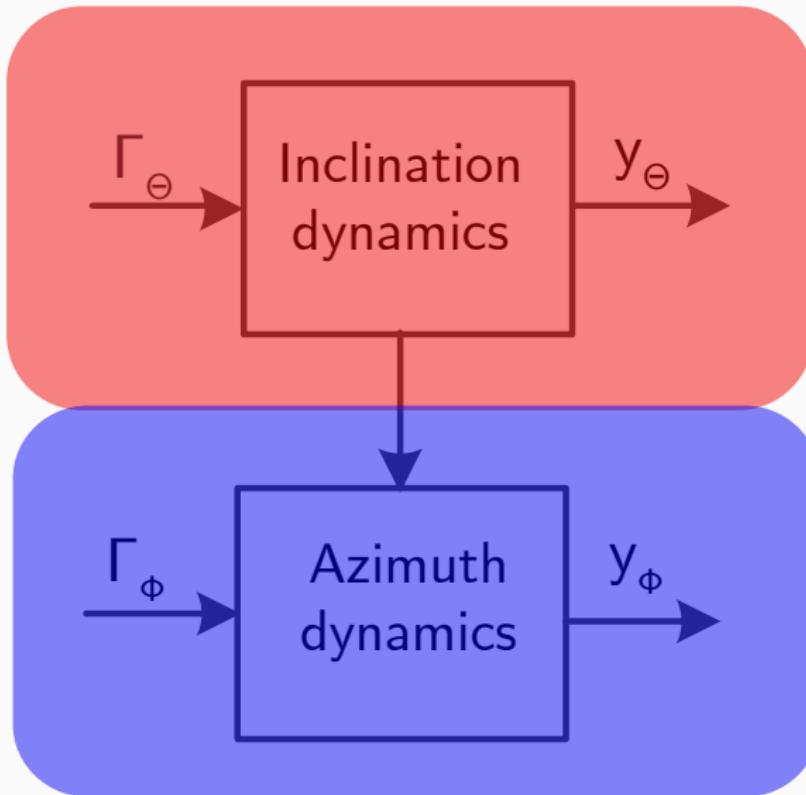
## Control objectives

- Track a desired reference trajectory corresponding to a complex borehole geometry
- The response of the system should have favorable transient behavior (avoid kinking, rippling and spiraling)

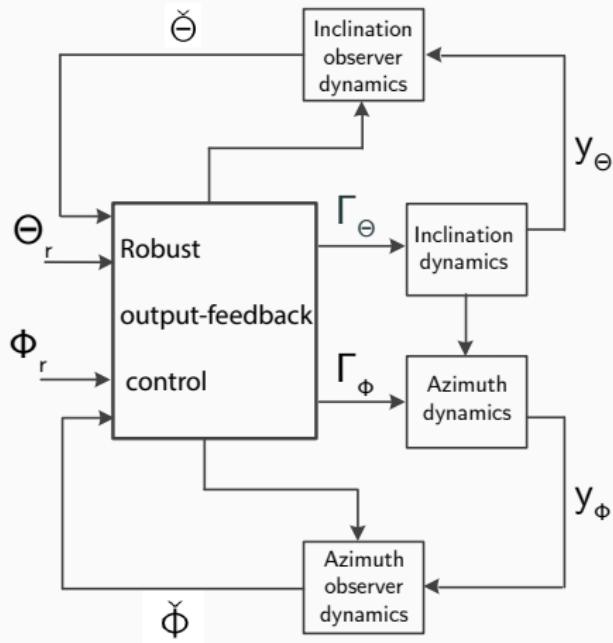
## Plant definition



## Plant definition



# Output-feedback strategy

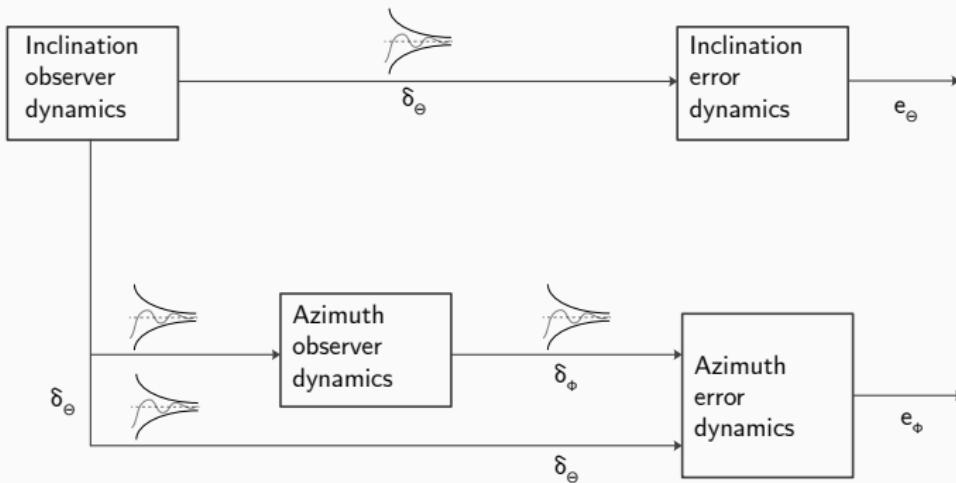


- Focus of the research: Include observer in the control structure
- Challenges
  - Nonlinear coupling between states while  $\Theta \neq \dot{\Theta}$
  - Controller and observer gain design

$$e_i := i_r - i \quad \delta_i := i - \dot{i} \quad \text{for } i = \Theta, \Phi$$

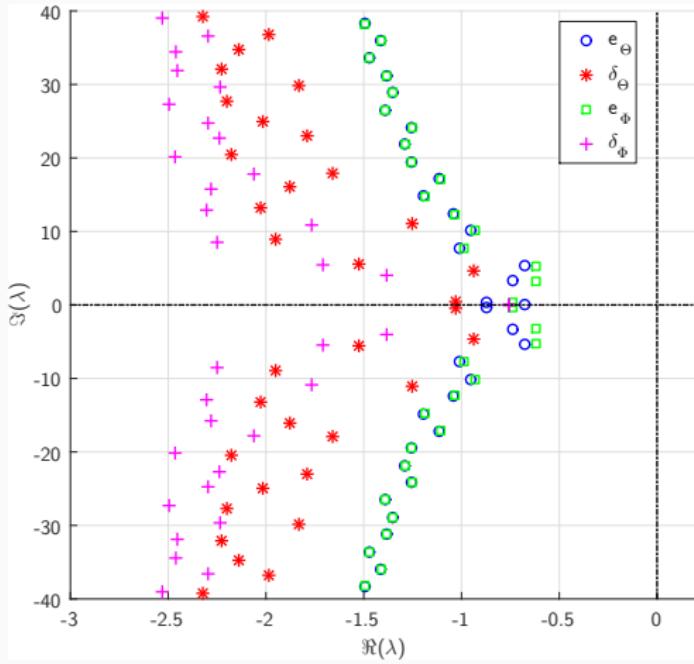
# Controller synthesis

- Define isolated systems  $e_\Theta$ ,  $\delta_\Theta$ ,  $e_\Phi$  and  $\delta_\Phi$
- Synthesize  $K_\Theta$ ,  $L_\Theta$ ,  $K_\Phi$  and  $L_\Phi$  for each isolated system separately
- Favorable transient performance

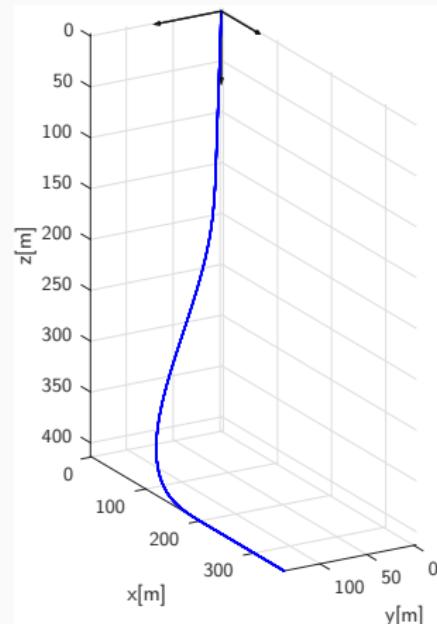
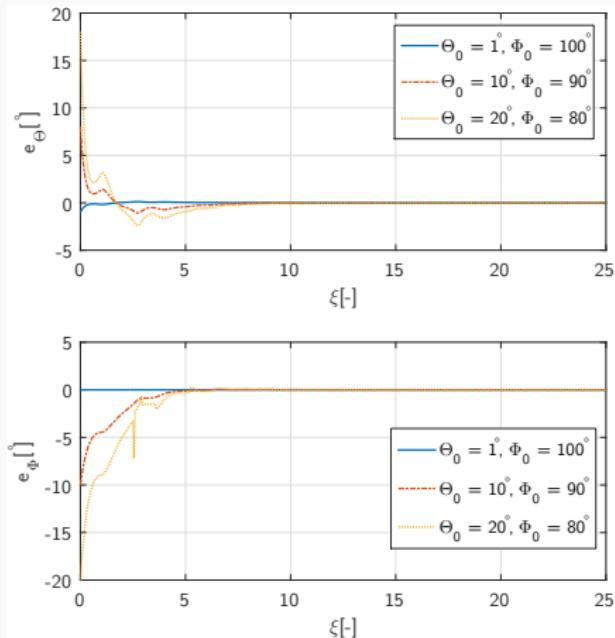


# Controller synthesis

- Infinite number of poles in delay systems (no pole-placement)
- Spectral approach [Michiels and Niculescu 2007]
- Optimize location of right-most pole over  $K_i$  (state-feedback gain) and  $L_i$  (observer-feedback gain)



# Simulation results



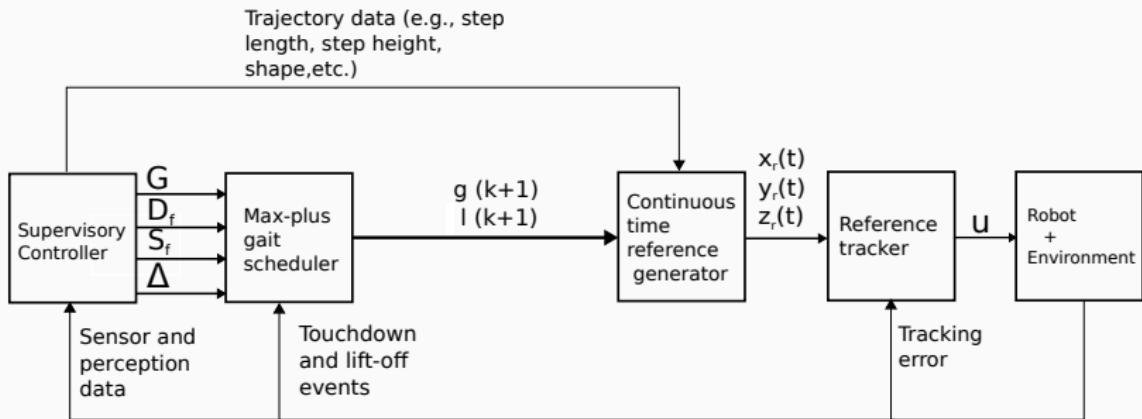
# **Research proposal: "Locomotion control of HyQ using max-plus algebra linear systems"**

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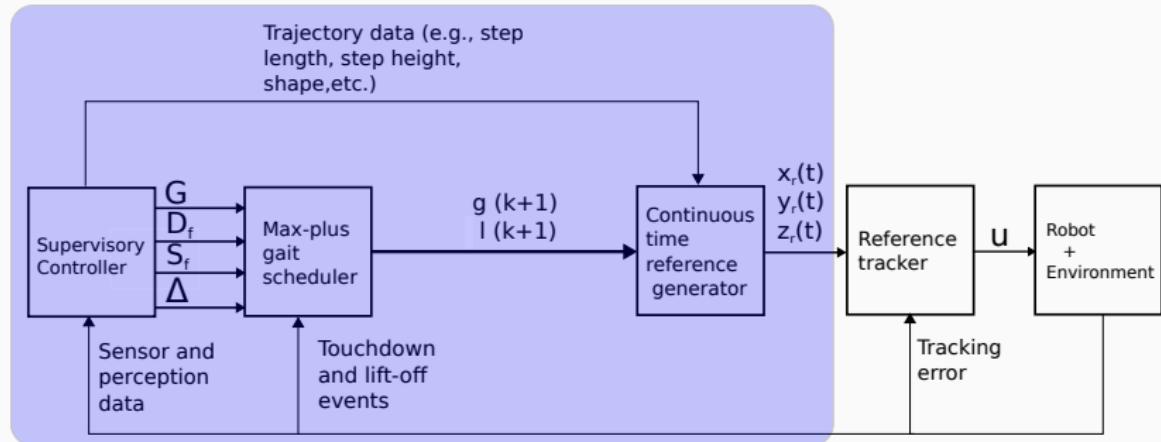
# Motivation

- Provide versatility to the types of gaits that the robot can perform
- Have a unified and systematic way to generate motions of the legs according to the scenario
- Can be applied to other legged systems

# General picture



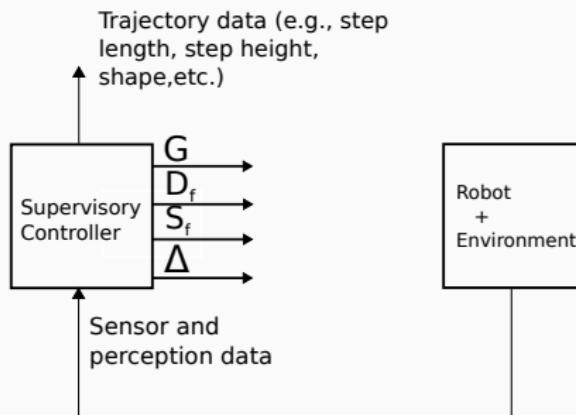
# General picture



# Supervisory controller

## Main goal

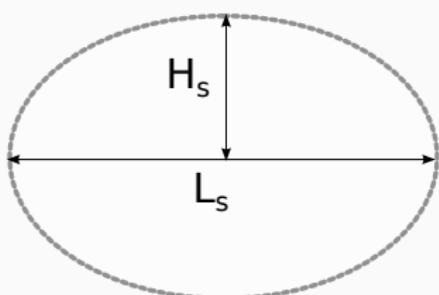
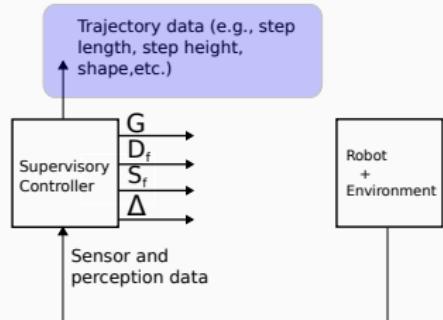
Decide **geometrical** and **time** gait parameters, based on sensory data, to overcome the scenario that the robot is facing.



# Geometrical parameters

- Not necessarily the same for all four legs

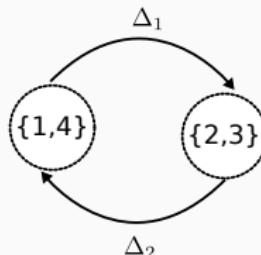
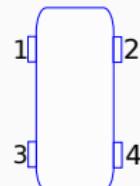
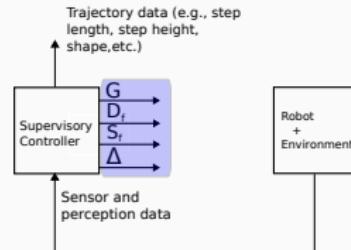
- Examples of trajectory parameters:
  - Oscillator shape parameters [Barasuol et.al. 2013]
  - Control points of a Bzier curve [Hyun et.al. 2014]



# Supervisory controller (continue)

Time parameters:

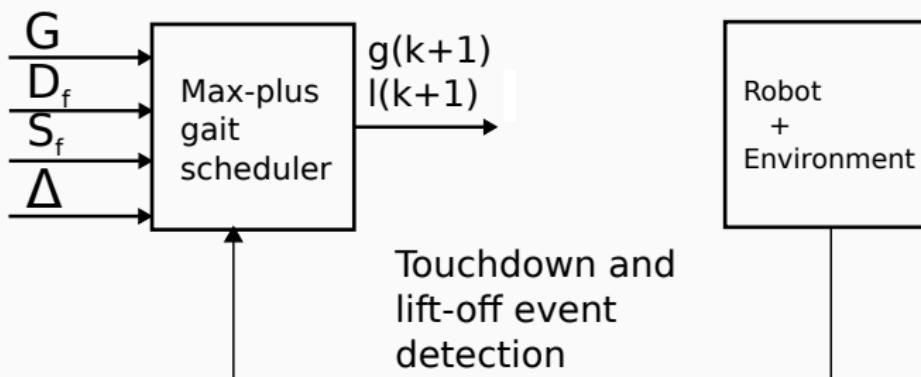
- Duty factor  $D_f$
- Step frequency  $S_f$
- Gait parameterization  $G$  (e.g.,  
 $G_{trot} = \{1, 4\} \prec \{2, 3\}$ )
- Time difference vector  $\Delta$



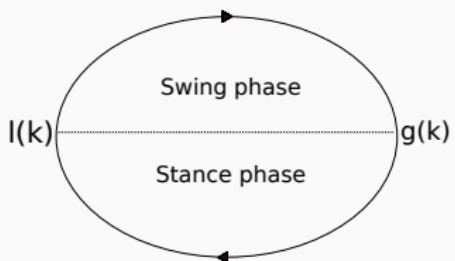
# Max-plus gait scheduler

## Main goal

Using the **time-related** gait parameters provided by the supervisory controller, generate the times that each leg has to touch or leave the ground.



## Max-plus gait scheduler (continue)



$$G_{trot} = \{1, 4\} \prec \{2, 3\}$$

$$D_f = 0.58$$

$$S_f = 0.42$$

$$\Delta = [0.2, 0.2]$$

$k$	$g_1(k)$	$g_2(k)$	$g_3(k)$	$g_4(k)$	$l_1(k)$	$l_2(k)$	$l_3(k)$	$l_4(k)$
0	0	0	0	0	0	0	0	0
1	2.4	3.6	3.6	2.4,	1.4	2.6	2.6	1.4
2	4.8	6	6	4.8	3.8	5	5	3.8
3	7.2	8.4	8.4	7.2	6.2	7.4	7.4	6.2
4	9.6	10.8	10.8	9.6	8.6	9.8	9.8	8.6
5	12	13.2	13.2	12	11	12.2	12.2	11

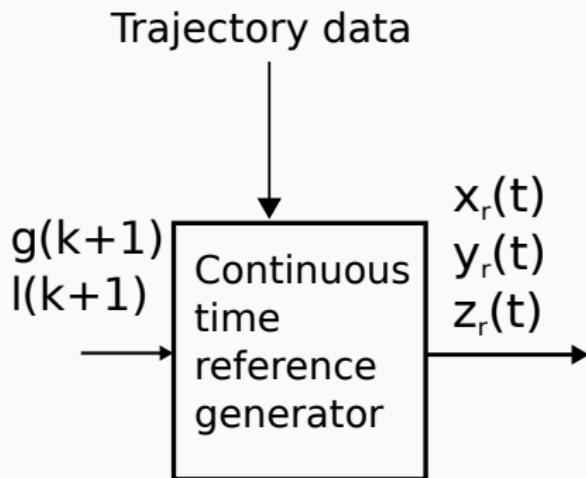
## Max-plus gait scheduler (continue)

- Systematic coordinated gait generation
- Total cycle time analysis (max-plus linear systems theory)
- Coupling time analysis ("settling time")
- Not computationally expensive

## Continuous reference generator

### Main goal

Making use of the **touchdown** and **lift-off** times of the max-plus gait scheduler, provide a reference trajectory for each of the legs.



## Continuous reference generator

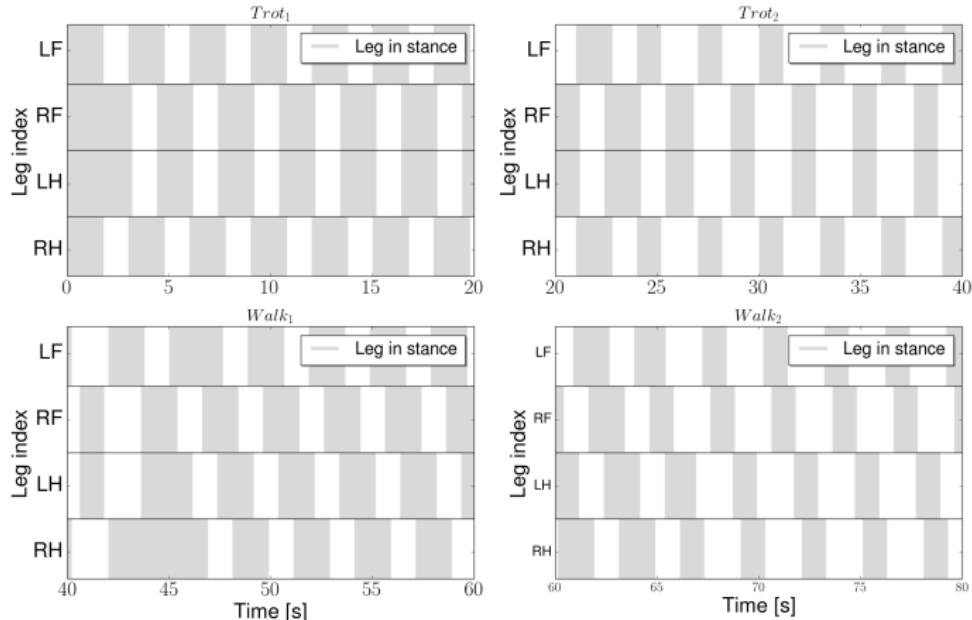
Possible alternatives:

- Oscillator with angular frequency modulation according to max-plus scheduler
- Parameterized velocity profile using lift-off  $l(k+1)$  and touchdown  $g(k+1)$  as initial and final times respectively

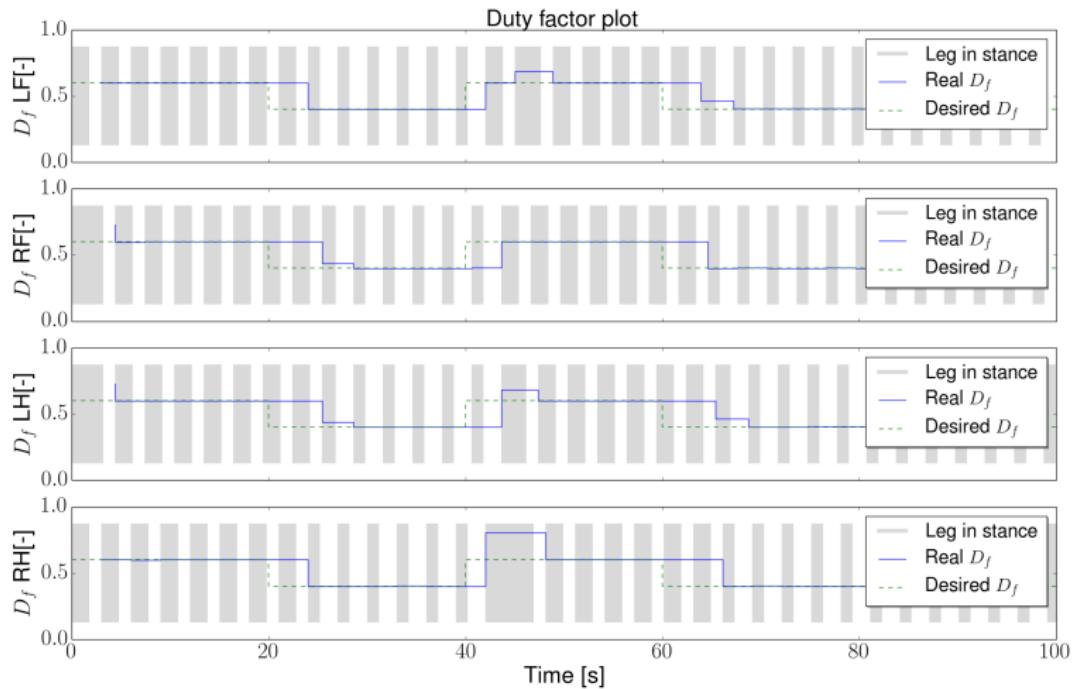
# Simulations

Change gait parameters every 20 seconds

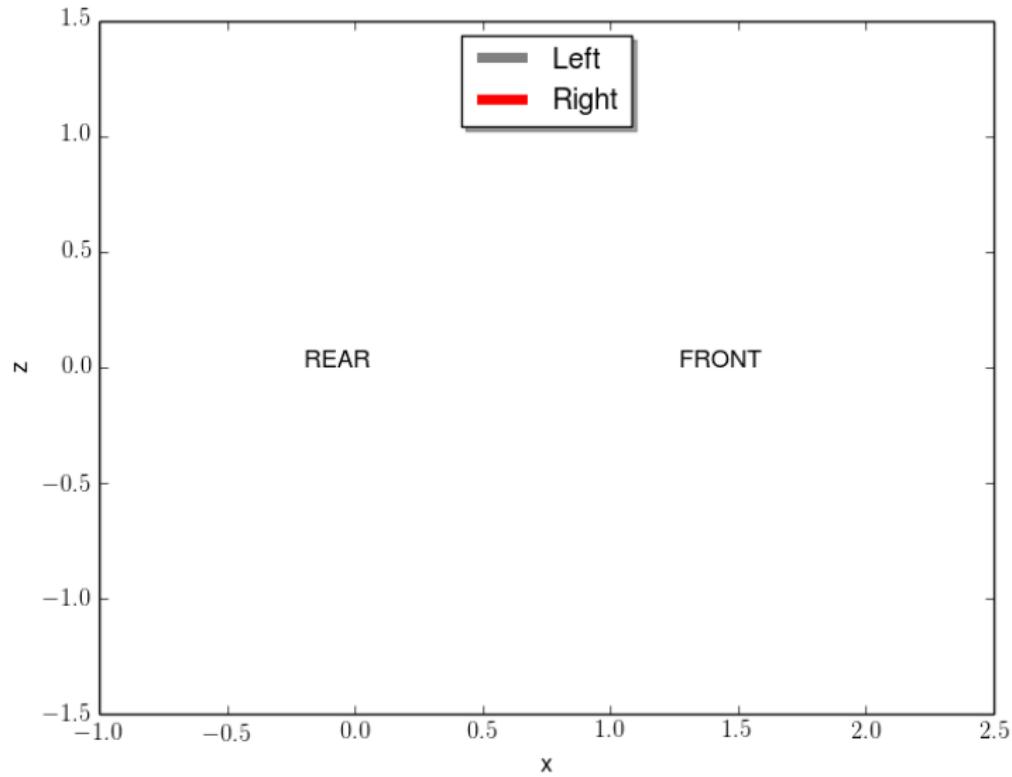
Plots for gaits with different parameters



# Duty factor



# Animation



Thank you. Questions or comments?