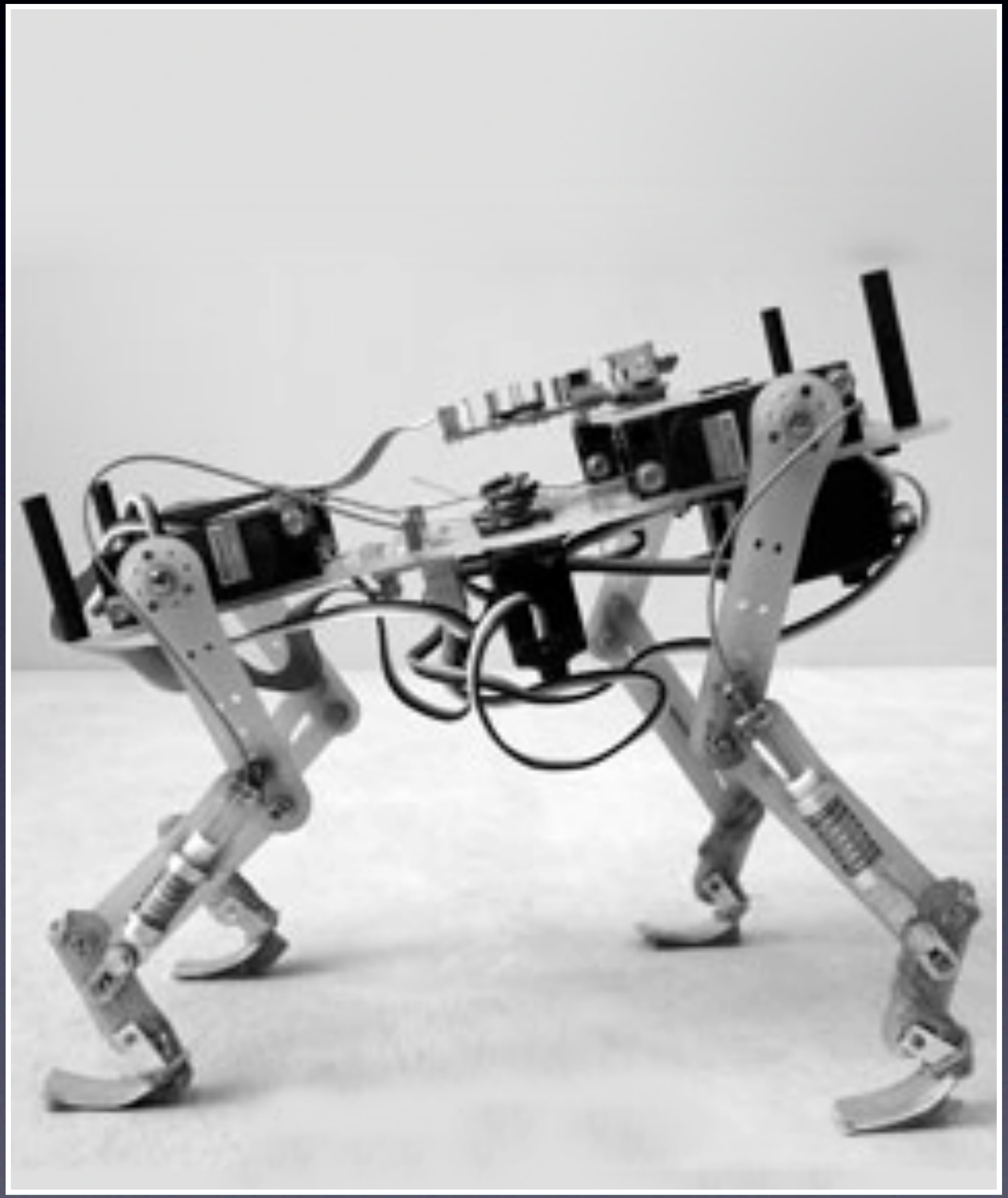
Improvement of the Cheetah Locomotion Control

Master Project - Final Presentation
15th February 2010

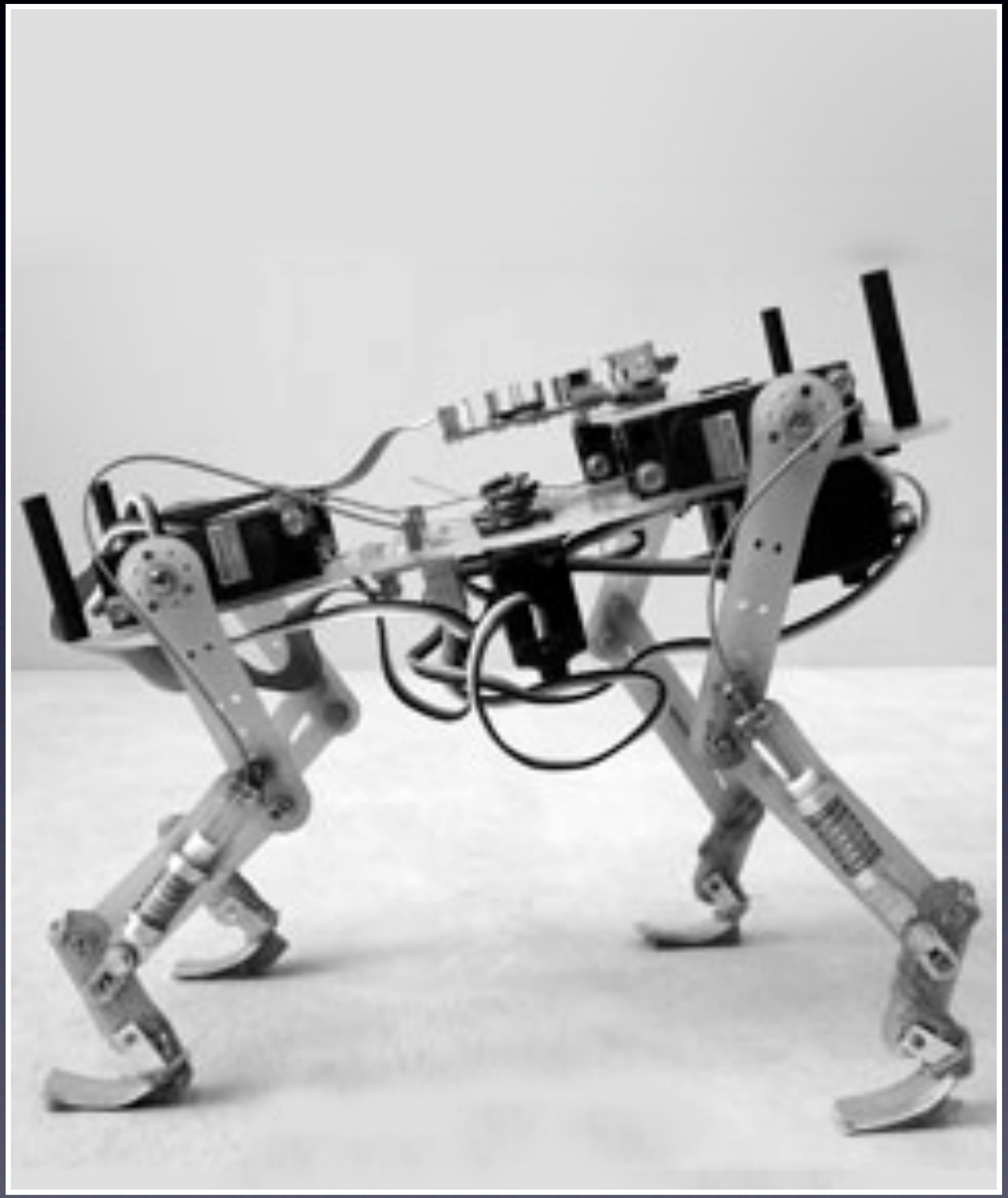
Student : Alexandre Tuleu
Supervisor : Alexander Spröwitz
Professor : Auke Jan Ijspeert

Presentation of the Cheetah



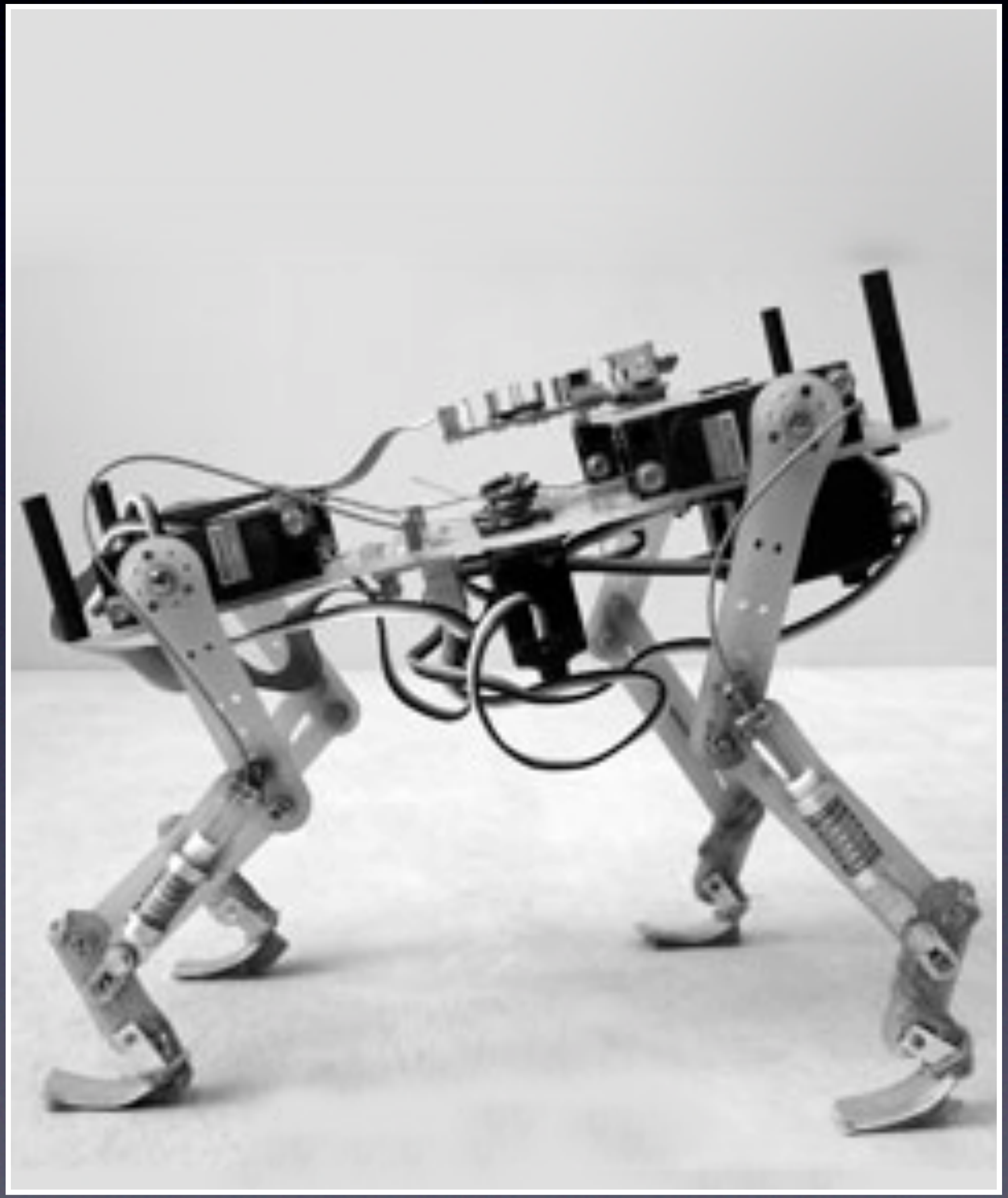
Presentation of the Cheetah

- Light weighted, biollogically inspired small quadruped robot



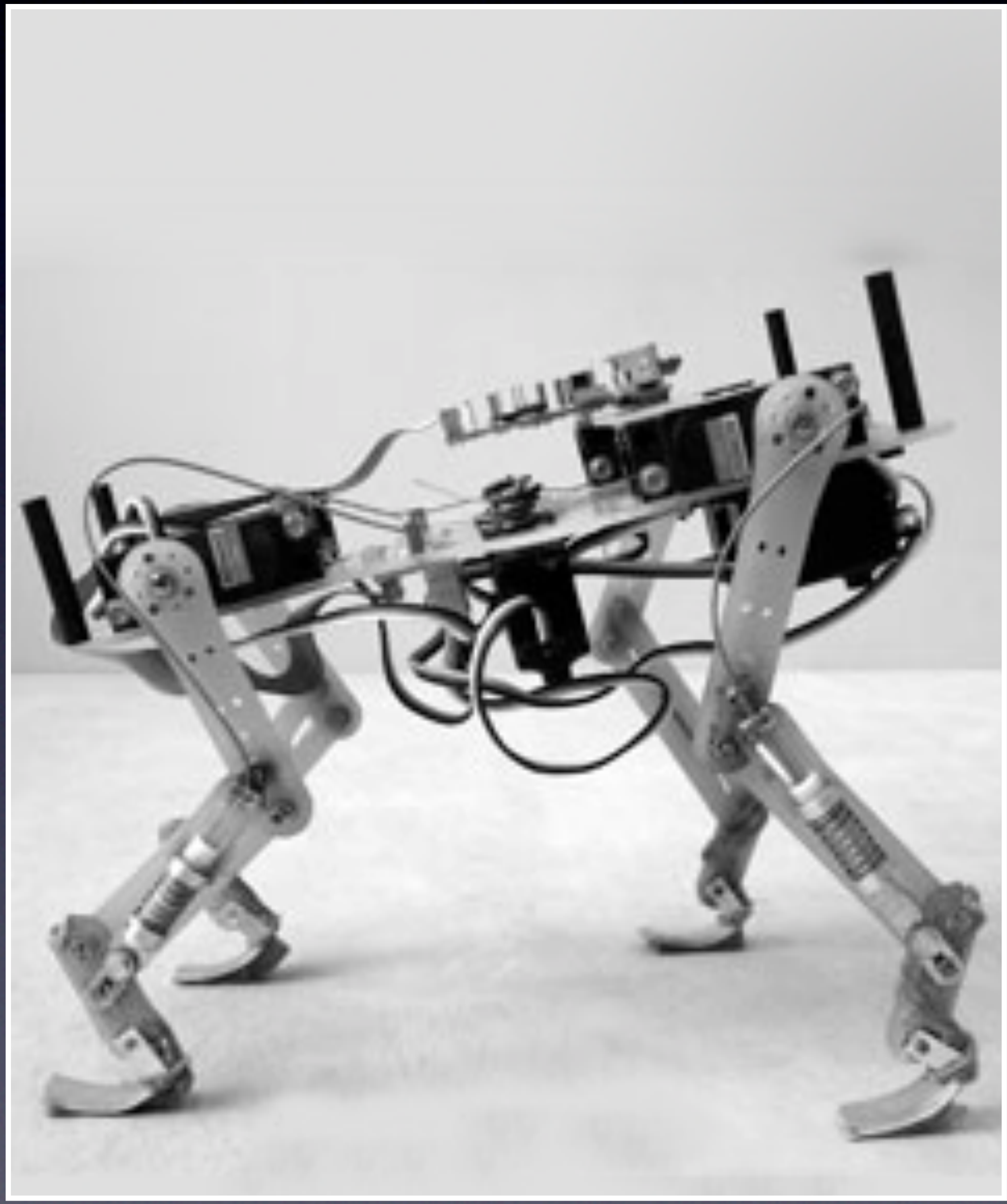
Presentation of the Cheetah

- Light weighted, biollogically inspired small quadruped robot
- Pantograph, compliant legs



Presentation of the Cheetah

- Light weighted, biollogically inspired small quadruped robot
- Pantograph, compliant legs
- Use CPG and Optimization Process for *offline learning*



Goals of the project

Goals of the project

- Improve the locomotion control in term of efficiency, Robustness and controllability

Goals of the project

- Improve the locomotion control in term of efficiency, Robustness and controllability
- Model mechanic improvement, and measure their effect on the locomotion behavior.

Table of contents

Table of contents

- Self-stabilization strategy in Nature

Table of contents

Table of contents

Table of contents

- Self-stabilization strategy in Nature
- Timeline of the project
- Update of the webots model
- CPG Design

Table of contents

Three Self-Stabilization Principles

[Seyfarth03] **Swing Leg Retraction: a simple control model for stable running**, André Seyfarth and Hartmut Geyer, *Journal of experimental Zoology* 206:2547-2555 (2003)
[Daley09] **The Role of Intrinsic muscle mechanics in the neuromuscular control of stable running in the guinea fowl**, *Journal of Physiology* 587.11 (2009) pp 2693-2707
Video Extract : Youtube

Three Self-Stabilization Principles

Self-Stabilization

Passive capacity to stabilize in open loop process (no sensory feed back as a response to internal or external disturbance)

[Seyfarth03] **Swing Leg Retraction: a simple control model for stable running**, André Seyfarth and Hartmut Geyer, *Journal of experimental Zoology* 206:2547-2555 (2003)
[Daley09] **The Role of Intrinsic muscle mechanics in the neuromuscular control of stable running in the guinea fowl**, *Journal of Physiology* 587.11 (2009) pp 2693-2707
Video Extract : Youtube

Three Self-Stabilization Principles

Self-Stabilization

Passive capacity to stabilize in open loop process (no sensory feed back as a response to internal or external disturbance)

- Leg Stiffening

[Seyfarth03] **Swing Leg Retraction: a simple control model for stable running**, André Seyfarth and Hartmut Geyer, *Journal of experimental Zoology* 206:2547-2555 (2003)
[Daley09] **The Role of Intrinsic muscle mechanics in the neuromuscular control of stable running in the guinea fowl**, *Journal of Physiology* 587.11 (2009) pp 2693-2707
Video Extract : Youtube

Three Self-Stabilization Principles

Self-Stabilization

Passive capacity to stabilize in open loop process (no sensory feed back as a response to internal or external disturbance)

- Leg Stiffening
- Leg Retraction [Seyfarth03]

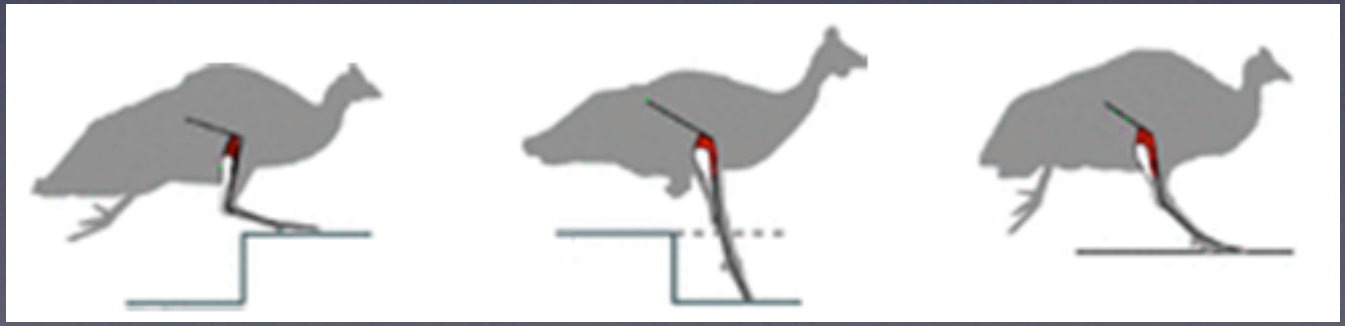
[Seyfarth03] **Swing Leg Retraction: a simple control model for stable running**, André Seyfarth and Hartmut Geyer, *Journal of experimental Zoology* 206:2547-2555 (2003)
[Daley09] **The Role of Intrinsic muscle mechanics in the neuromuscular control of stable running in the guinea fowl**, *Journal of Physiology* 587.11 (2009) pp 2693-2707
Video Extract :Youtube

Three Self-Stabilization Principles

Self-Stabilization

Passive capacity to stabilize in open loop process (no sensory feed back as a response to internal or external disturbance)

- Leg Stiffening
- Leg Retraction [Seyfarth03]
- Leg Extension [Daley09]



[Seyfarth03] **Swing Leg Retraction: a simple control model for stable running**, André Seyfarth and Hartmut Geyer, *Journal of experimental Zoology* 206:2547-2555 (2003)
[Daley09] **The Role of Intrinsic muscle mechanics in the neuromuscular control of stable running in the guinea fowl**, *Journal of Physiology* 587.11 (2009) pp 2693-2707
Video Extract : Youtube

Timeline

Model Update		Design of the control		Testing Mechanical Improvement		
Fix Webots Model	Prepare optimization framework	Foot trajectory definition	Gait Optimization	New Foot	New Scapula Joint	Sipnal Cord

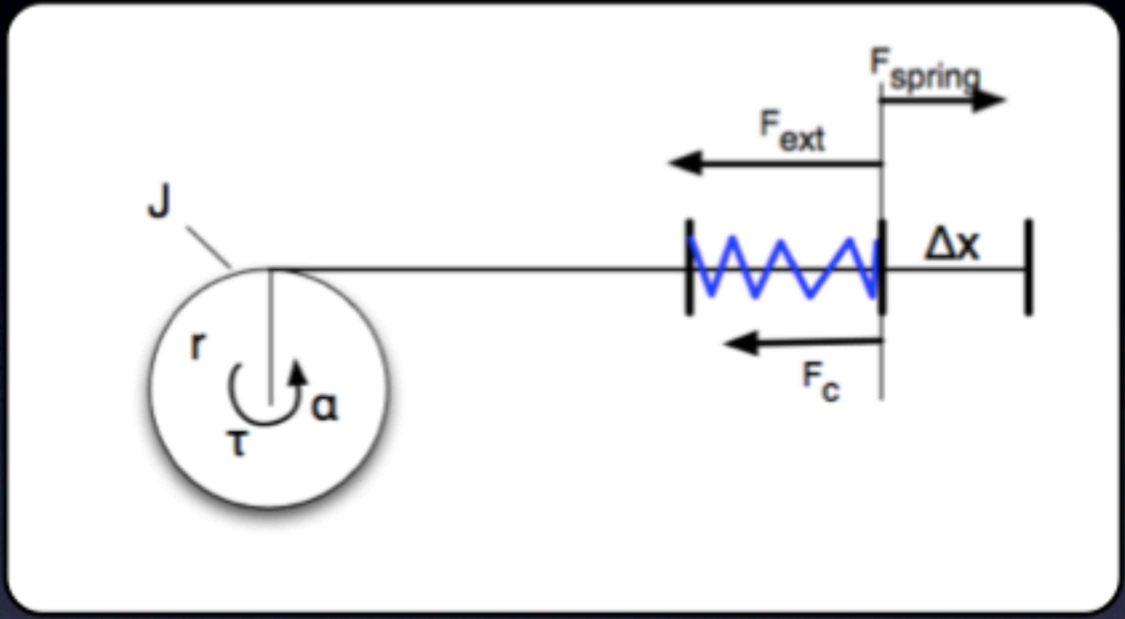
Timeline

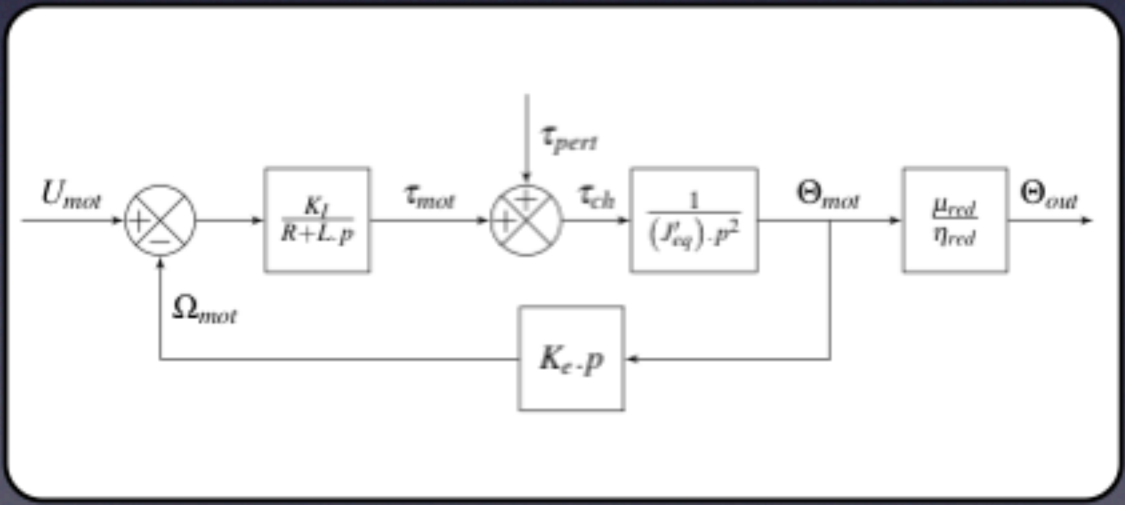
Model Update		Design of the control		Testing Mechanical Improvement		
Fix Webots Model	Prepare optimization framework	Foot trajectory definition	Gait Optimization	New Foot	New Scapula Joint	Sipnal Cord

Timeline

Model Update		Design of the control		Testing Mechanical Improvement		
Fix Webots Model	Prepare optimization framework	Foot trajectory definition	Gait Optimization	New Foot	New Scapula Joint	Sipnal Cord

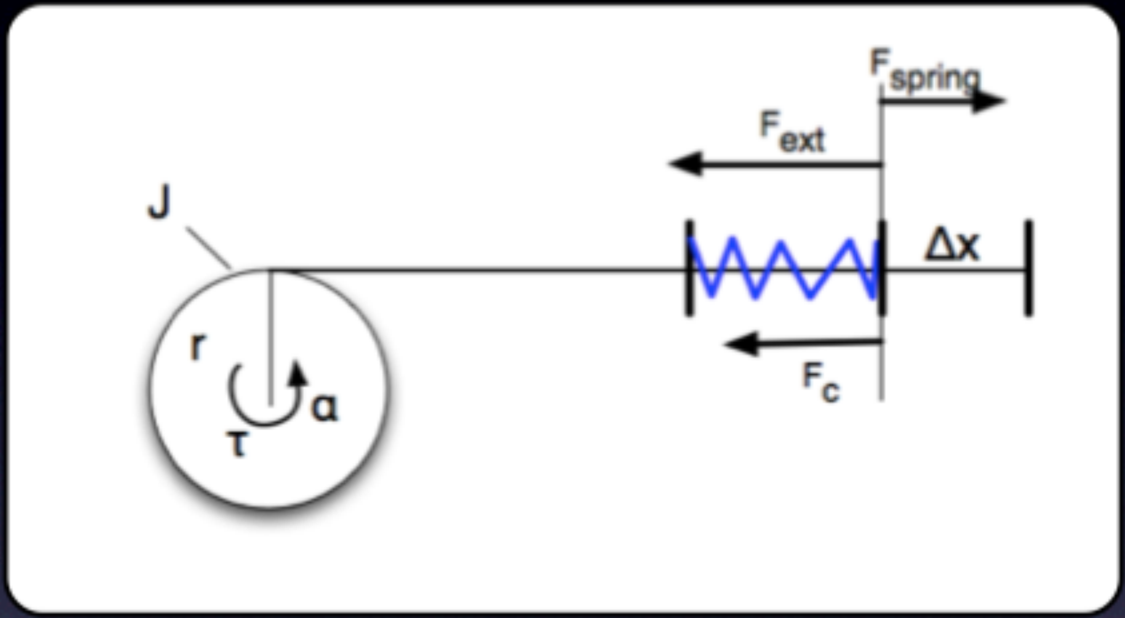
Modelisation of the Knee

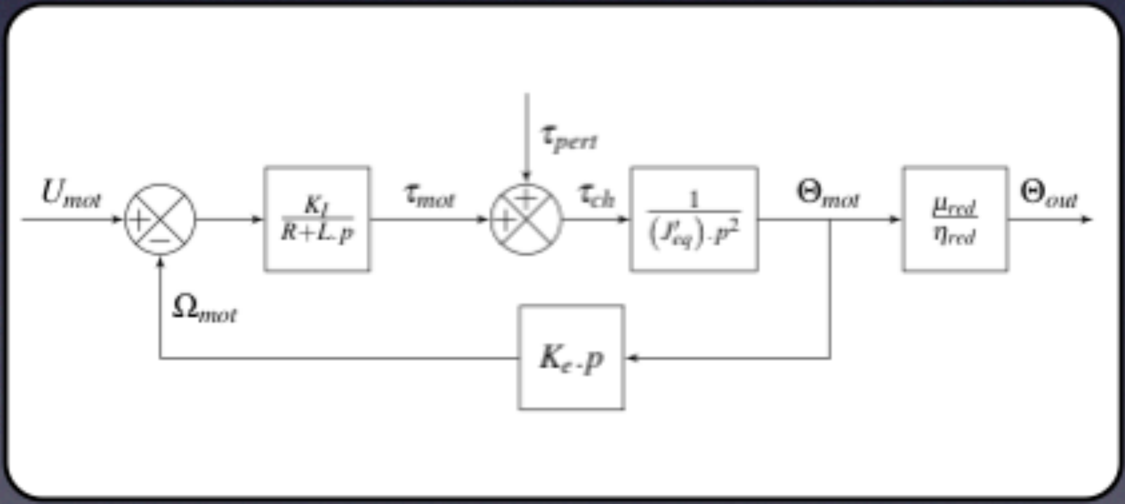




Modelisation of the Knee

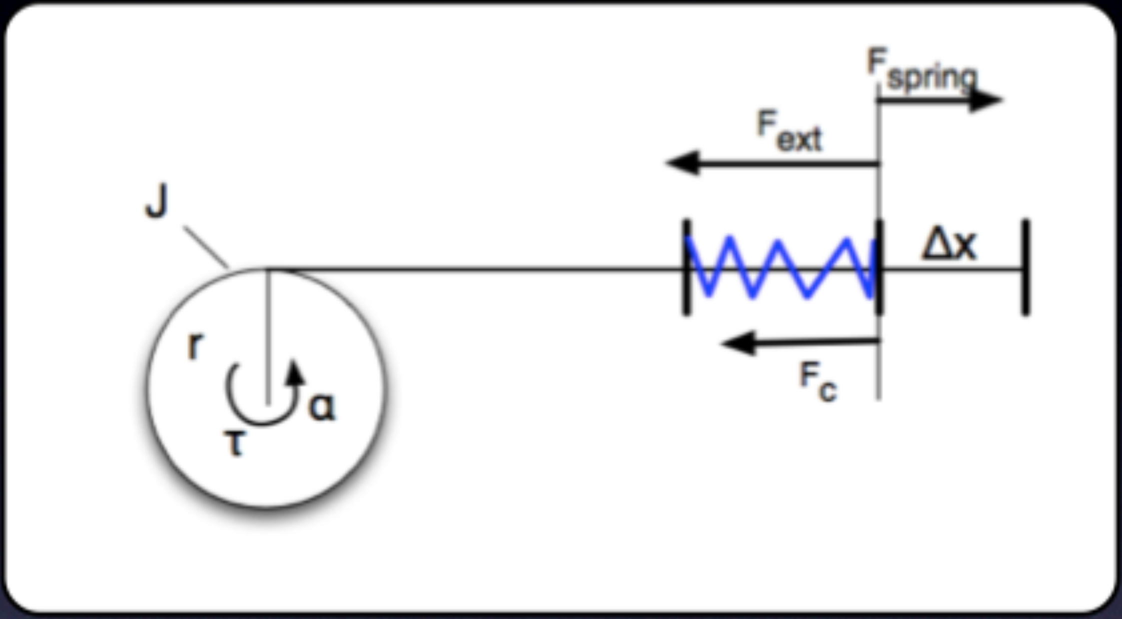
- Enhanced Model of the Knee Servo motor implemented

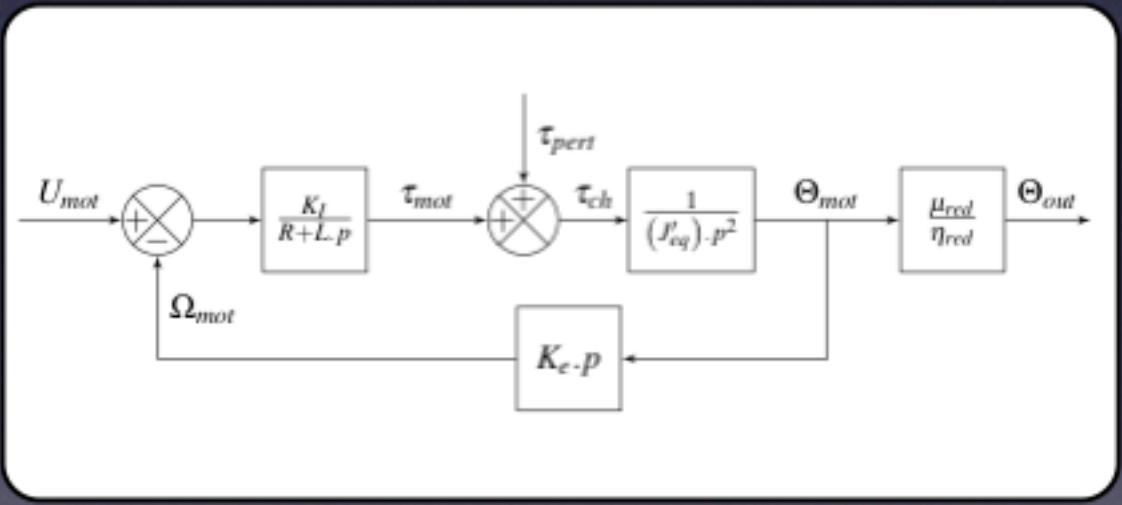




Modelisation of the Knee

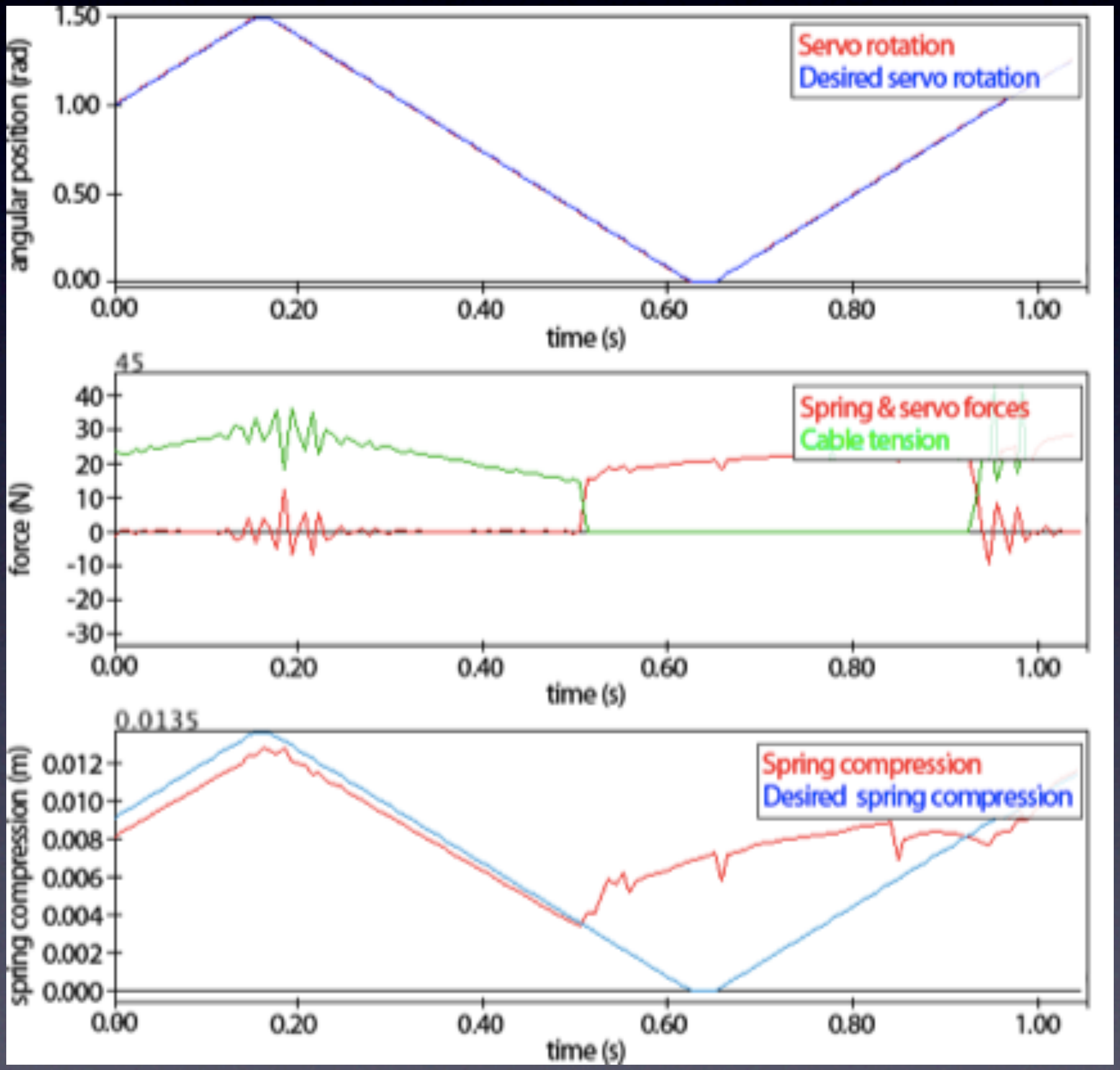
- Enhanced Model of the Knee Servo motor implemented
- Bowden cable modeled as an assymetrical spring





Modelisation of the Knee

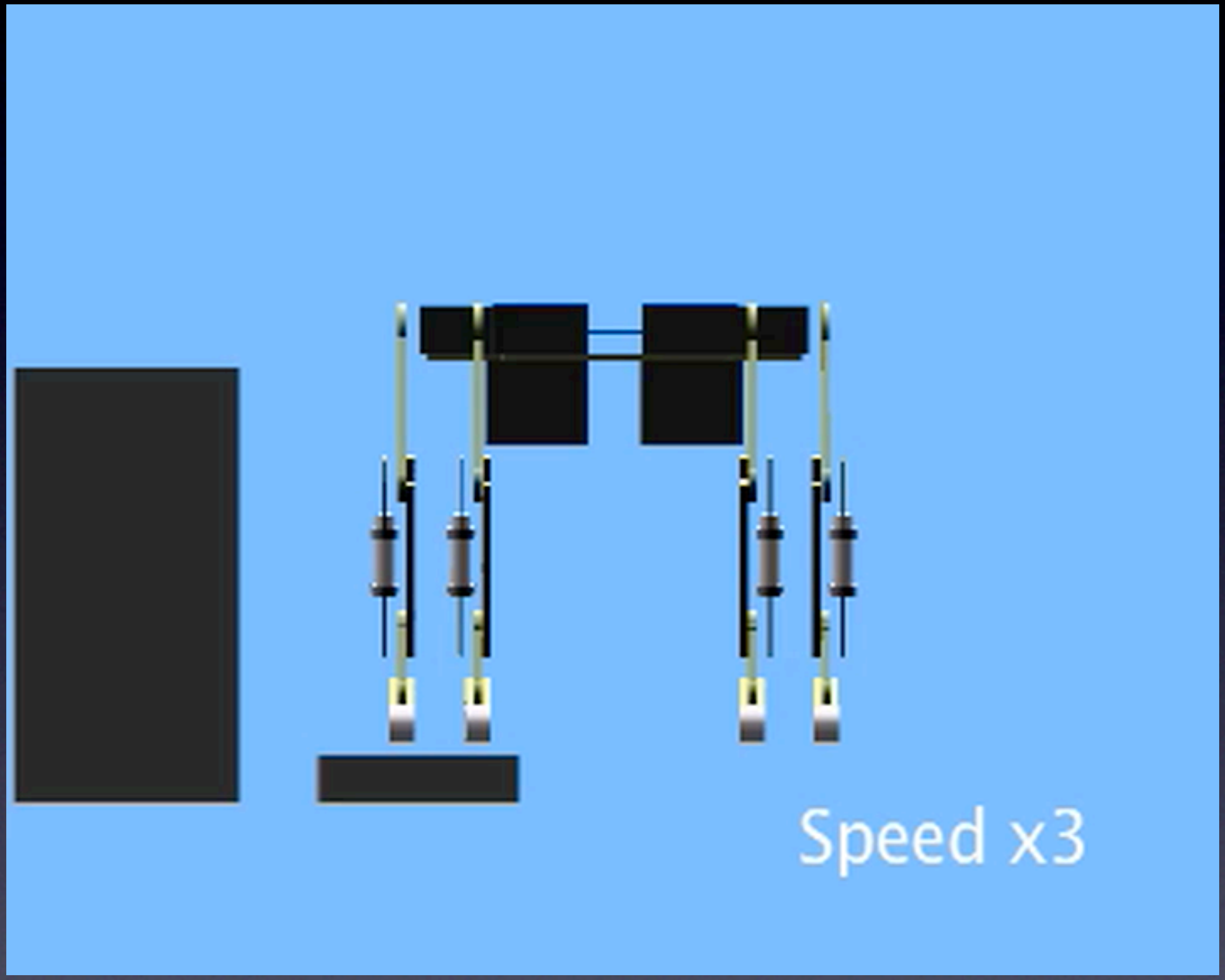
- Enhanced Model of the Knee Servo motor implemented
- Bowden cable modeled as an assymetrical spring
- Further Improvement : decrease timestep integration with a loop



ODE unrealistic behavior

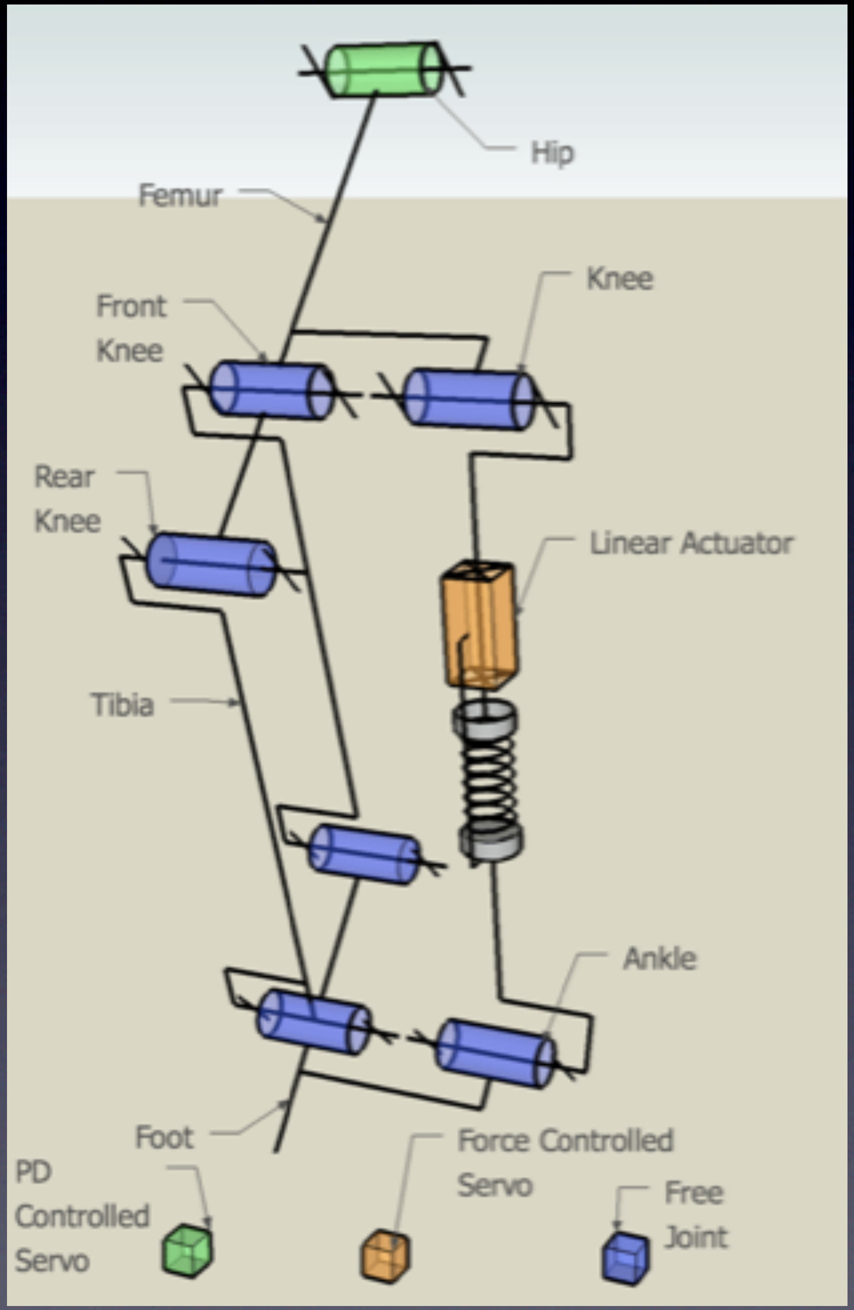
Previous solution : tuning the ODE CFM parameter.

ODE unrealistic behavior

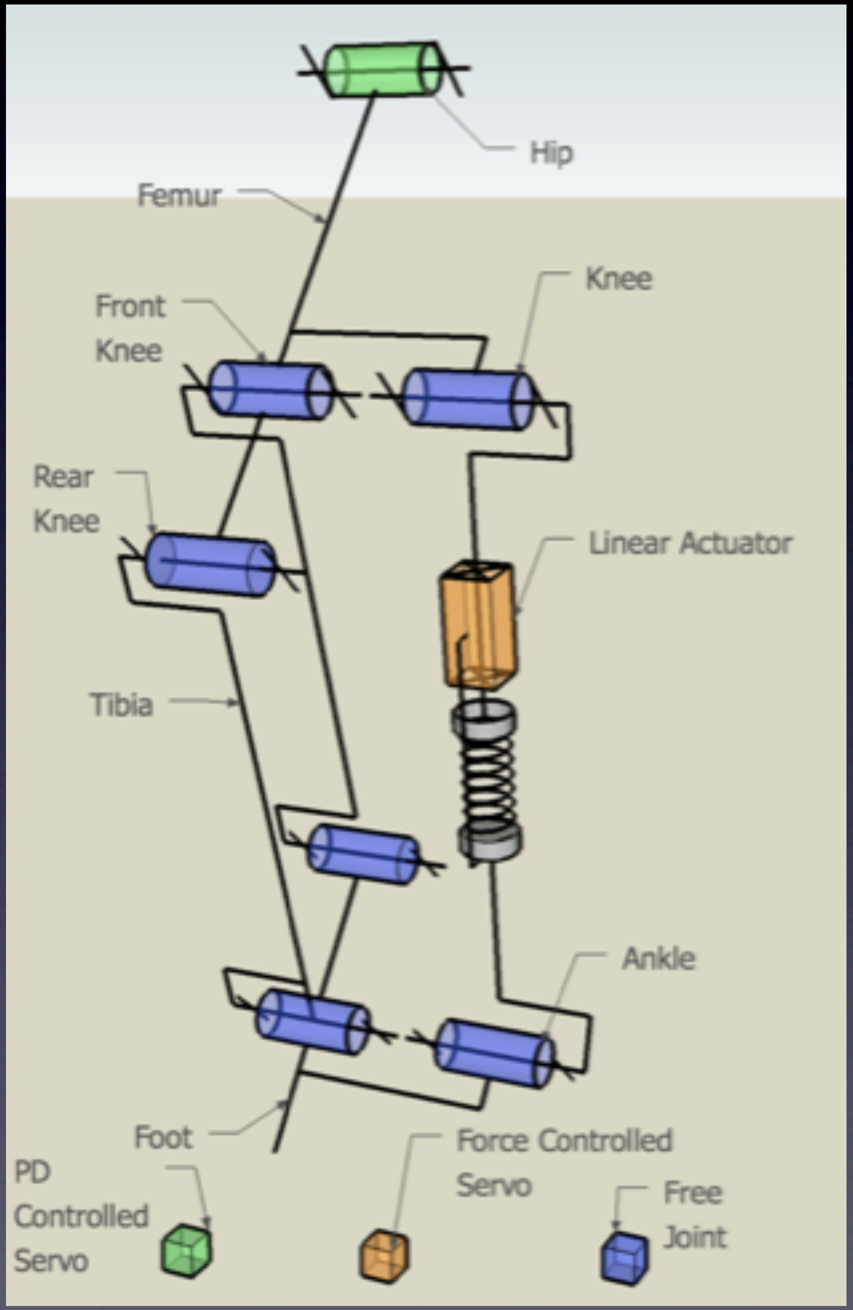


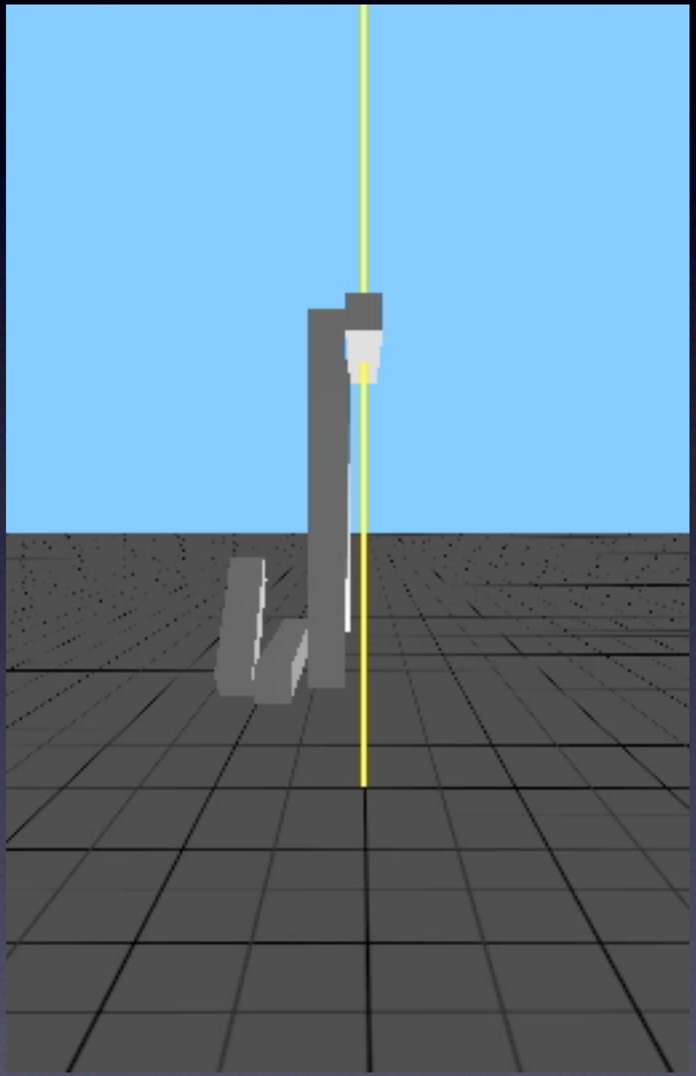
Previous solution : tuning the ODE CFM parameter.

Releasing the overconstraint

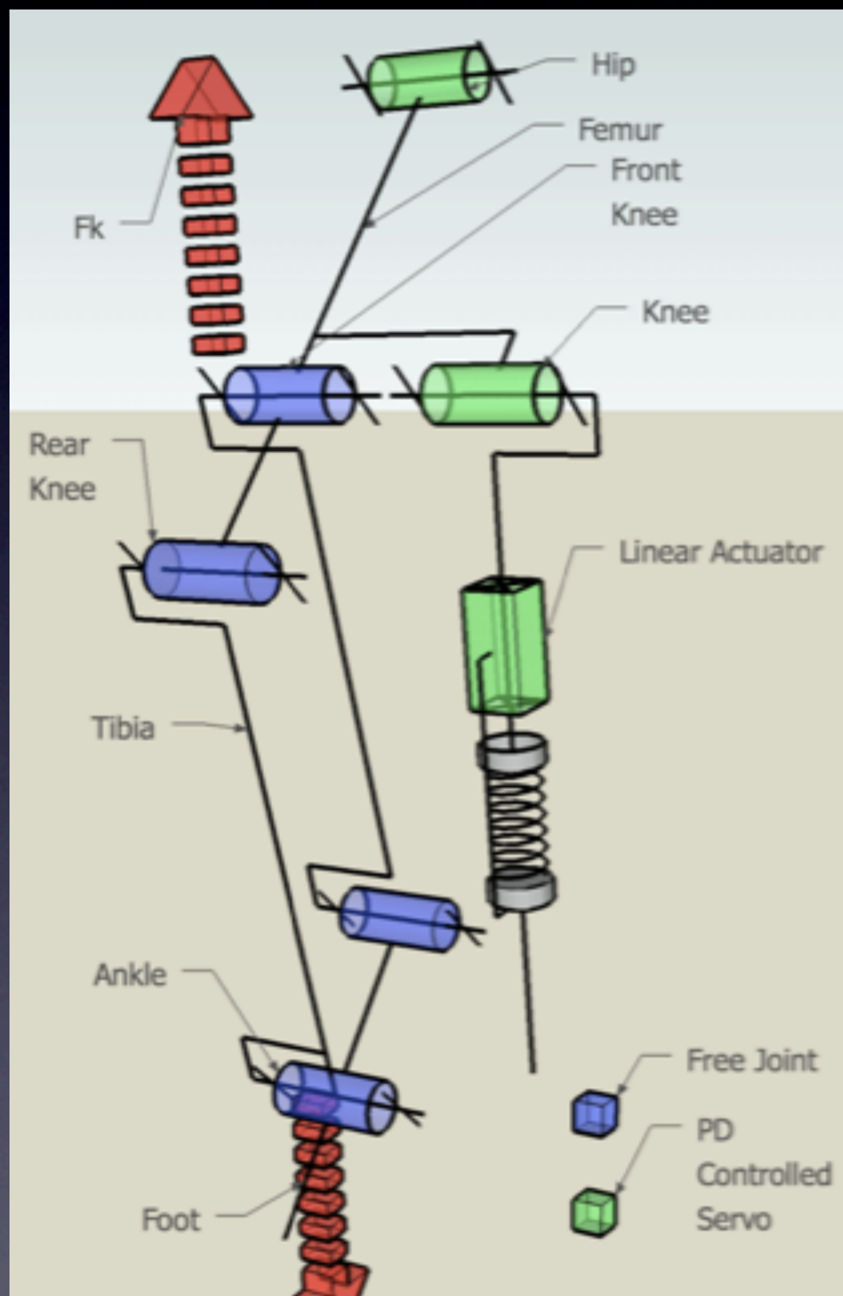


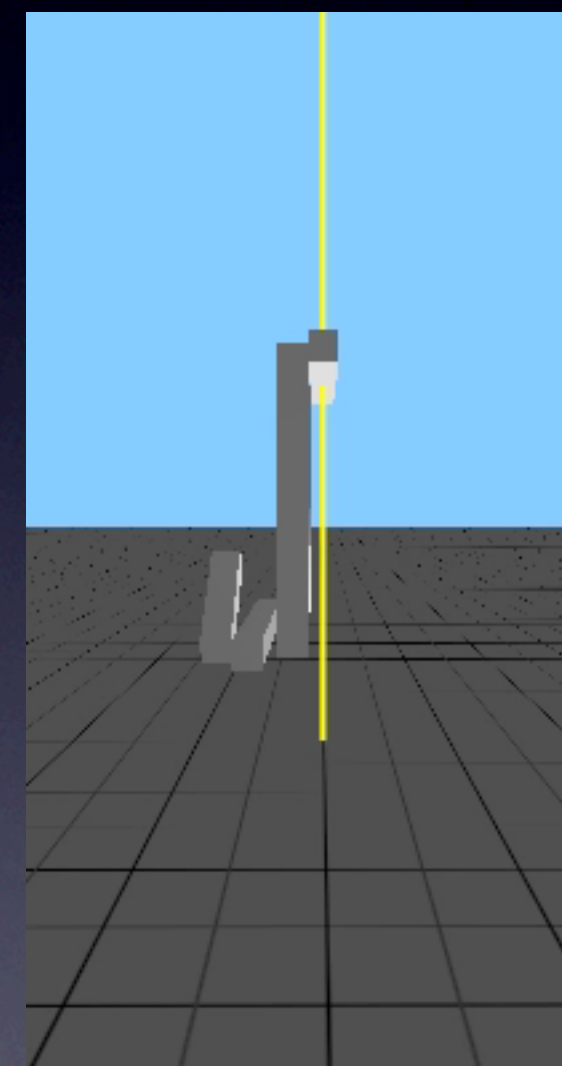
Releasing the overconstraint





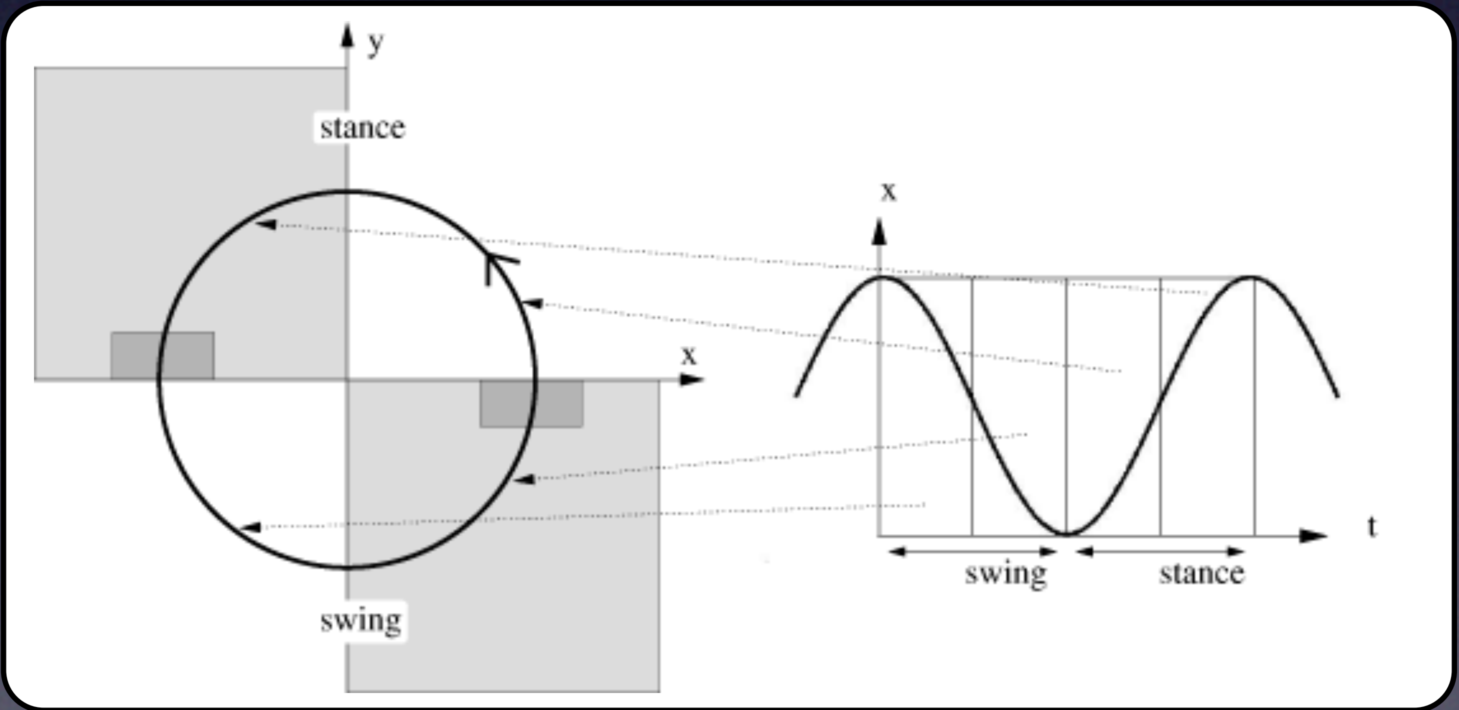
Releasing the overconstraint





Ludovic Righetti CPG

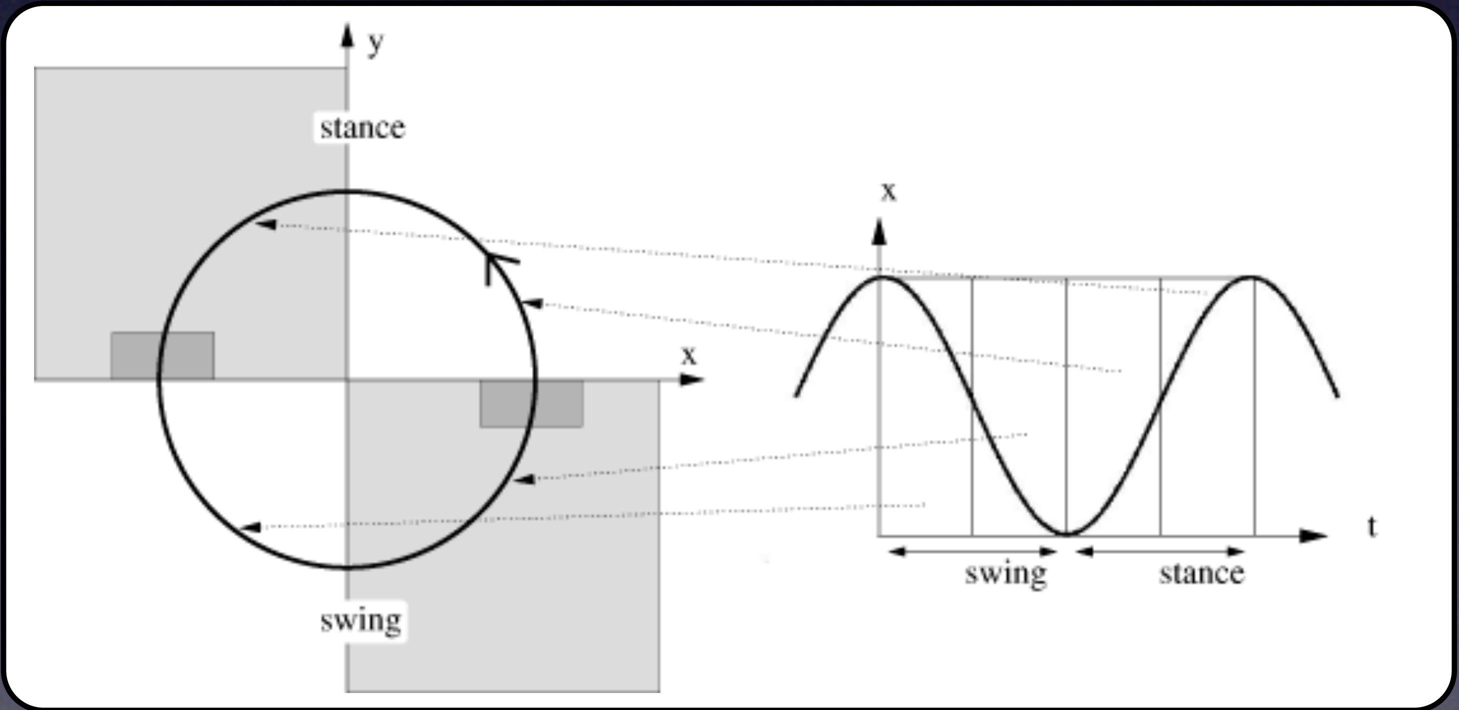
$$\begin{aligned}\dot{x}_i &= \alpha(\mu - r^2)x_i - \omega_i y_i \\ \dot{y}_i &= \beta(\mu - r^2)y_i + \omega_i x_i + \sum_{j \neq i} k_{ij} y_j \\ \omega_i &= \frac{\omega_{st}}{1+e^{by}} + \frac{\omega_{sw}}{1+e^{-by}}\end{aligned}$$



Ludovic Righetti CPG

- Can generate several gait : walk trot pace bound.

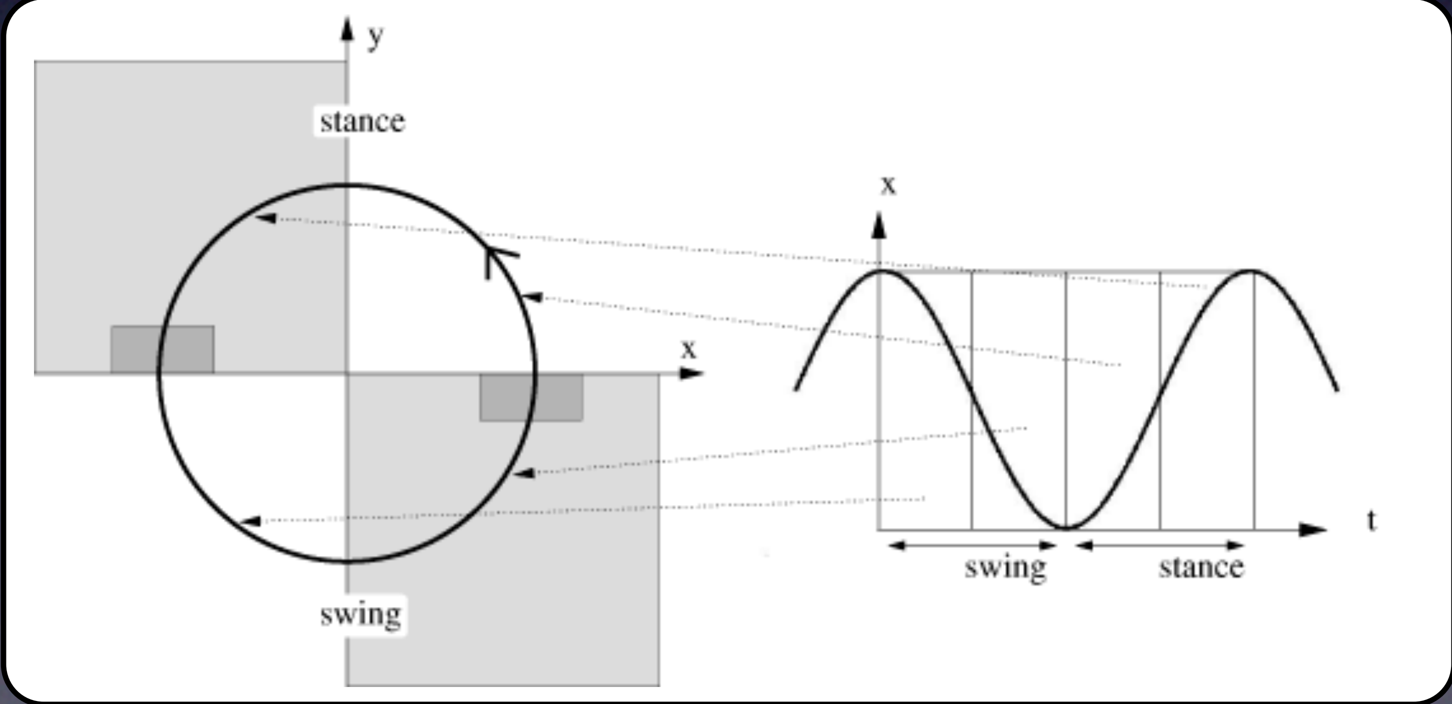
$$\begin{aligned} \dot{x}_i &= \alpha(\mu - r^2)x_i - \omega_i y_i \\ \dot{y}_i &= \beta(\mu - r^2)y_i + \omega_i x_i + \sum_{j \neq i} k_{ij} y_j \\ \omega_i &= \frac{\omega_{st}}{1 + e^{by}} + \frac{\omega_{sw}}{1 + e^{-by}} \end{aligned}$$



Ludovic Righetti CPG

- Can generate several gait : walk trot pace bound.
- Can modulate the duty ratio

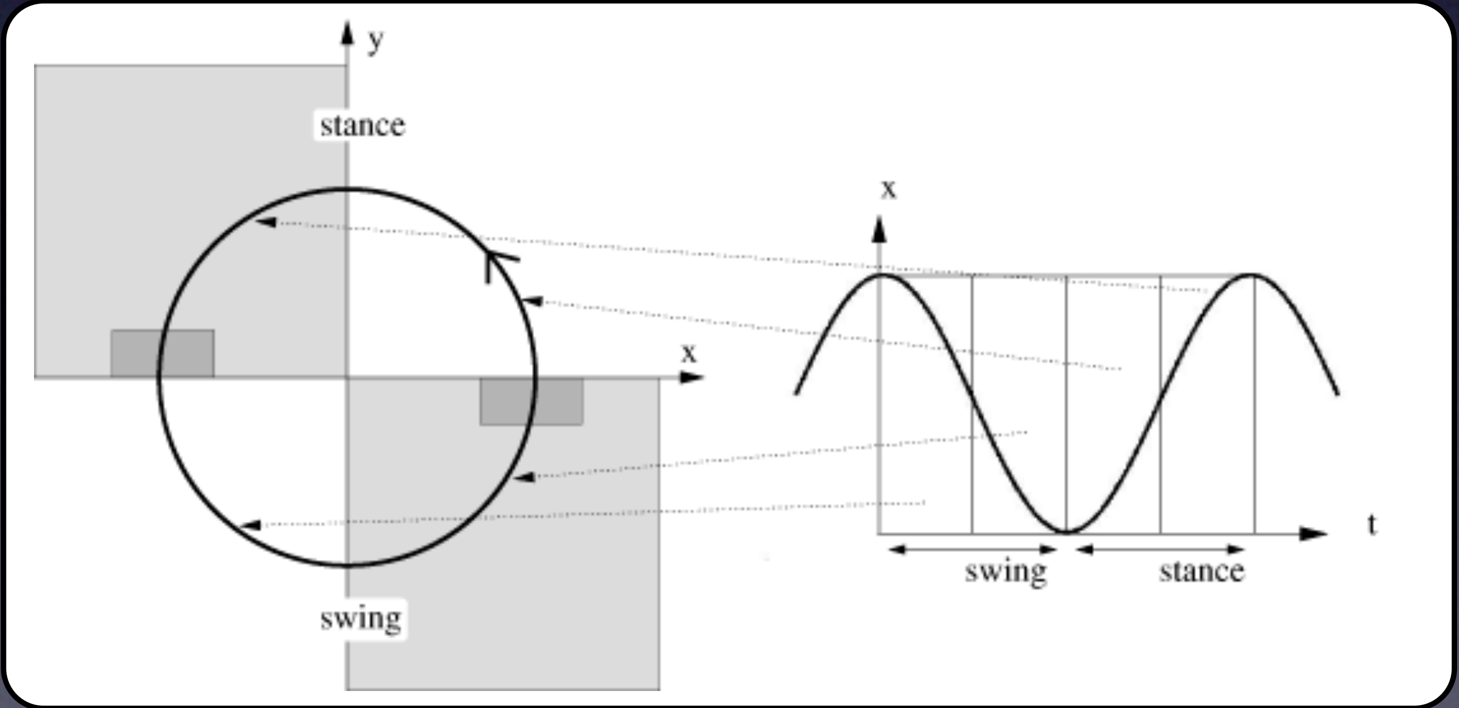
$$\begin{aligned} \dot{x}_i &= \alpha(\mu - r^2)x_i - \omega_i y_i \\ \dot{y}_i &= \beta(\mu - r^2)y_i + \omega_i x_i + \sum_{j \neq i} k_{ij} y_j \\ \omega_i &= \frac{\omega_{st}}{1+e^{by}} + \frac{\omega_{sw}}{1+e^{-by}} \end{aligned}$$



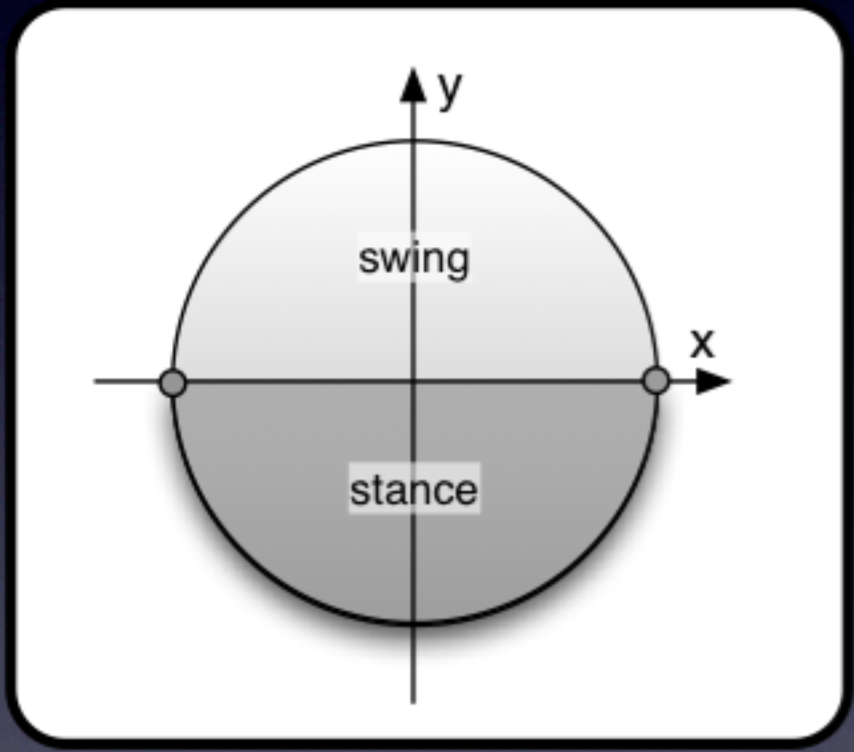
Ludovic Righetti CPG

- Can generate several gait : walk trot pace bound.
- Can modulate the duty ratio
- Uses sensory feedback information

$$
\begin{aligned}
\dot{x}_i &= \alpha(\mu - r^2)x_i - \omega_i y_i \\
\dot{y}_i &= \beta(\mu - r^2)y_i + \omega_i x_i + \sum_{j \neq i} k_{ij} y_j \\
\omega_i &= \frac{\omega_{st}}{1 + e^{by}} + \frac{\omega_{sw}}{1 + e^{-by}}
\end{aligned}
$$

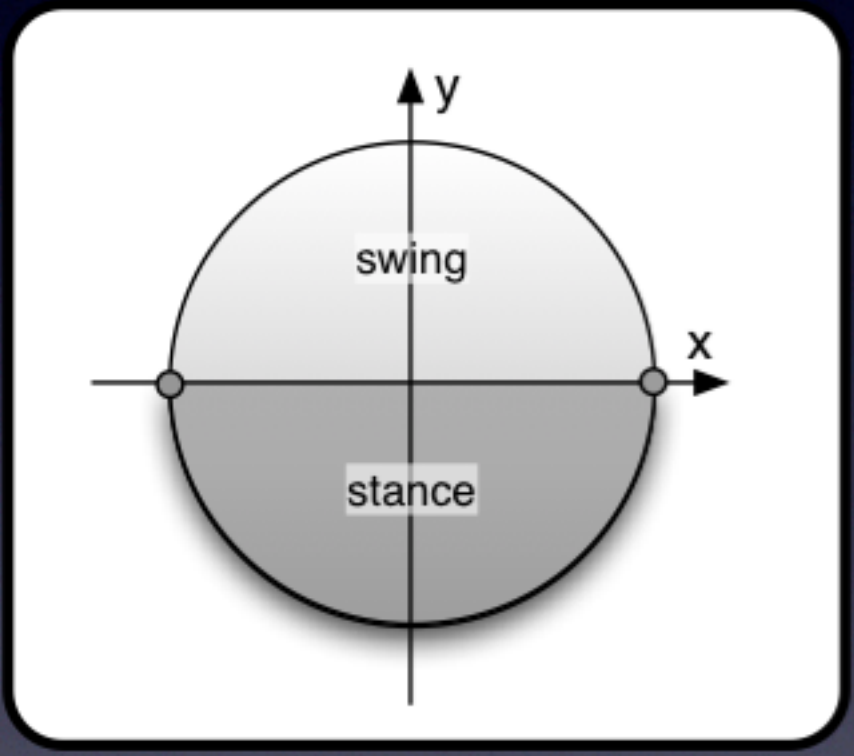


Adding leg retraction strategy to CPG



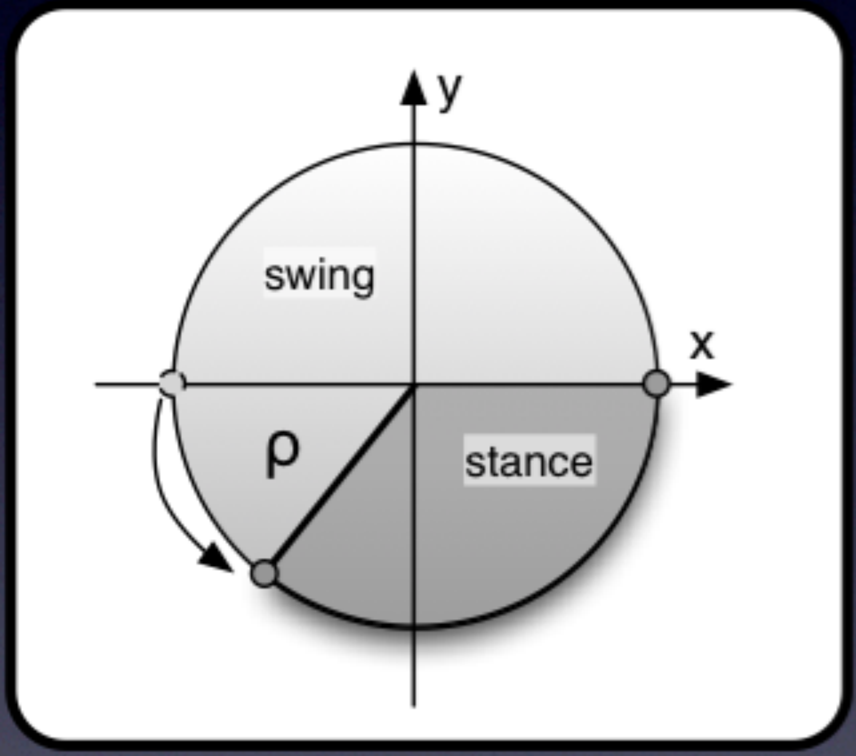
Adding leg retraction strategy to CPG

- Need to have a non-zero horizontal velocity at touchdown



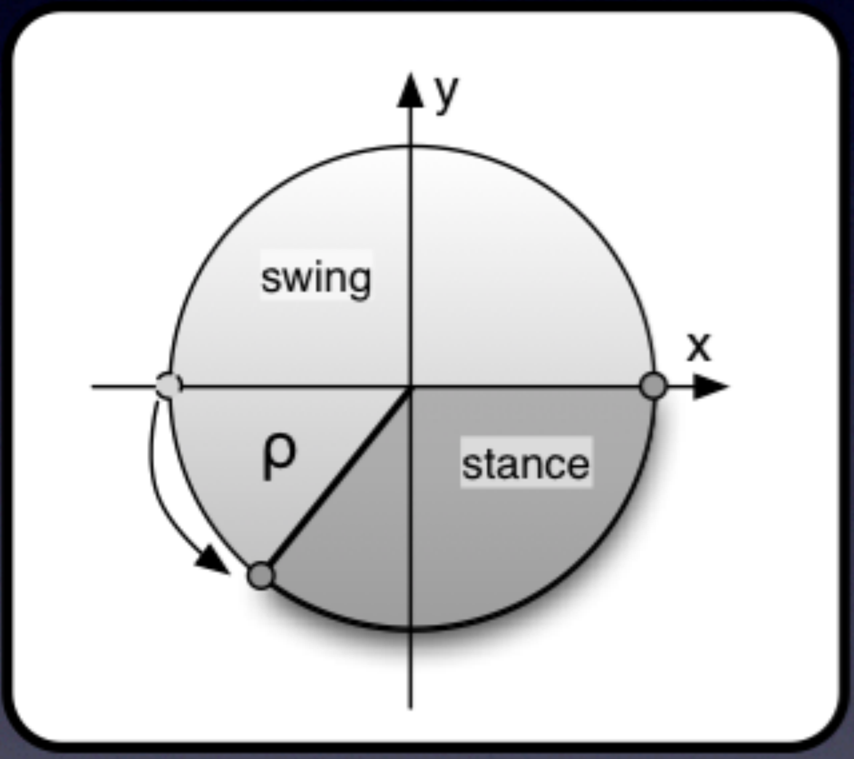
Adding leg retraction strategy to CPG

- Need to have a non-zero horizontal velocity at touchdown
  - Moves the swing to stance transition point.



Adding leg retraction strategy to CPG

- Need to have a non-zero horizontal velocity at touchdown
  - Moves the swing to stance transition point.
- Just change the phase output.

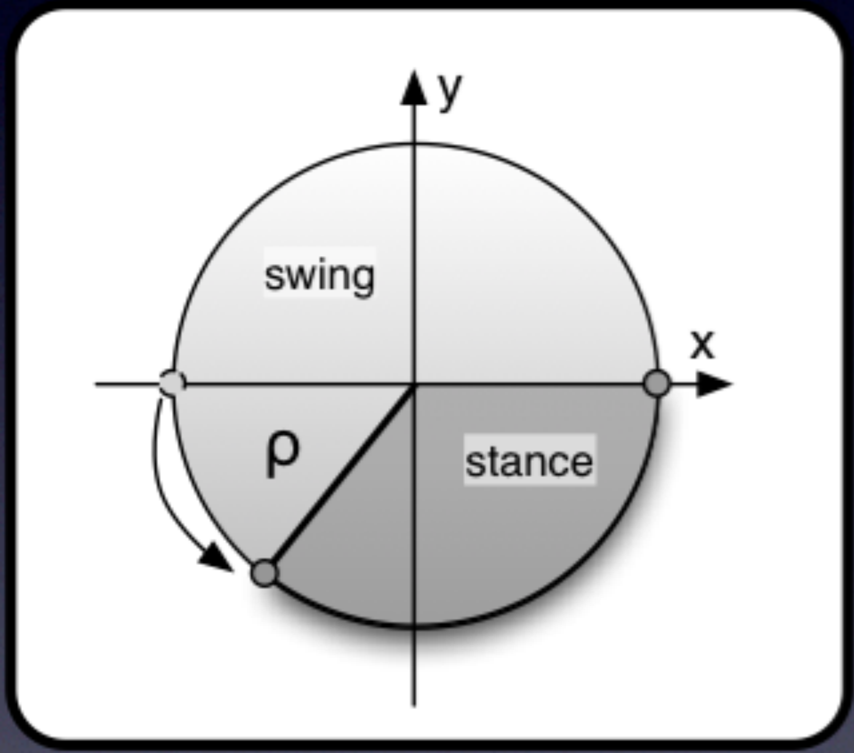


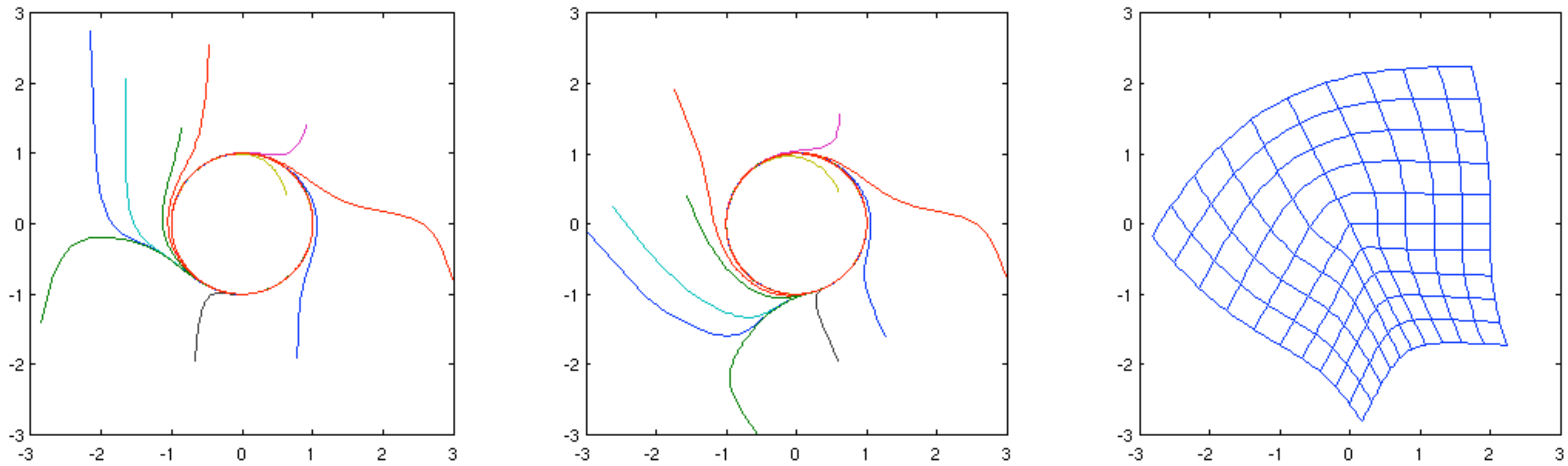
Adding leg retraction strategy to CPG

- Need to have a non-zero horizontal velocity at touchdown
  - Moves the swing to stance transition point.
- Just change the phase output.
- Transformation of the phase in polar coordinate.

$$\begin{aligned} \mathbf{R}^+ \times [-\pi, \pi] &\to \mathbf{R}^+ \times [-\pi, \pi] \\ \begin{bmatrix} r \\ \theta \end{bmatrix} &\mapsto \begin{bmatrix} r \\ f_\rho(\theta) \end{bmatrix} \end{aligned}$$

$$f_\rho(\theta) = -\rho.\left(\frac{\theta}{\pi}\right)^4 + 2.\rho.\left(\frac{\theta}{\pi}\right)^2 + \theta$$





Original trajectories Tansformed trajectories Tansformed mesh

$$\mathbf{R}^+ \times [-\pi, \pi] \to \mathbf{R}^+ \times [-\pi, \pi]$$

$$\begin{bmatrix} r \\ \theta \end{bmatrix} \mapsto \begin{bmatrix} r \\ f_\rho(\theta) \end{bmatrix}$$

$$f_\rho(\theta) = -\rho . \left(\frac{\theta}{\pi}\right)^4 + 2.\rho . \left(\frac{\theta}{\pi}\right)^2 + \theta$$

Optimization Definiton

Name	Boundaries
Hip::duty	$[0.05, 0.95]$
Fore::Hip::amplitude	$[0.0, 2.0]$
Fore::Hip::offset	$[-1.3, 0.9]$
Fore::Hip::refraction	$\left[0.0, \frac{\pi}{2}\right]$
Hind::Hip::amplitude	$[0.0, 2.0]$
Hind::Hip::offset	$[-1.3, 0.9]$
Hind::Hip::refraction	$\left[0.0, \frac{\pi}{2}\right]$
Fore::Knee::amplitude	$\left[0.0, \frac{\pi}{2}\right]$
Fore::Knee::ThExtension	$\left[\frac{\pi}{2}, \frac{3\pi}{2}\right]$
Fore::Knee::ThContraction	$\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$
Hind::Knee::amplitude	$\left[0.0, \frac{\pi}{2}\right]$
Hind::Knee::ThExtension	$\left[\frac{\pi}{2}, \frac{3\pi}{2}\right]$
Hind::Knee::ThContraction	$\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$

Optimization Definiton

- Using Particle Swarm Optimization

Name	Boundaries
Hip::duty	$[0.05, 0.95]$
Fore::Hip::amplitude	$[0.0, 2.0]$
Fore::Hip::offset	$[-1.3, 0.9]$
Fore::Hip::refraction	$\left[0.0, \frac{\pi}{2}\right]$
Hind::Hip::amplitude	$[0.0, 2.0]$
Hind::Hip::offset	$[-1.3, 0.9]$
Hind::Hip::refraction	$\left[0.0, \frac{\pi}{2}\right]$
Fore::Knee::amplitude	$\left[0.0, \frac{\pi}{2}\right]$
Fore::Knee::ThExtension	$\left[\frac{\pi}{2}, \frac{3\pi}{2}\right]$
Fore::Knee::ThContraction	$\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$
Hind::Knee::amplitude	$\left[0.0, \frac{\pi}{2}\right]$
Hind::Knee::ThExtension	$\left[\frac{\pi}{2}, \frac{3\pi}{2}\right]$
Hind::Knee::ThContraction	$\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$

Optimization Definiton

- Using Particle Swarm Optimization
- Differentiate between hindlimb and forelimb parameter

Name	Boundaries
Hip::duty	$[0.05, 0.95]$
Fore::Hip::amplitude	$[0.0, 2.0]$
Fore::Hip::offset	$[-1.3, 0.9]$
Fore::Hip::refraction	$\left[0.0, \frac{\pi}{2}\right]$
Hind::Hip::amplitude	$[0.0, 2.0]$
Hind::Hip::offset	$[-1.3, 0.9]$
Hind::Hip::refraction	$\left[0.0, \frac{\pi}{2}\right]$
Fore::Knee::amplitude	$\left[0.0, \frac{\pi}{2}\right]$
Fore::Knee::ThExtension	$\left[\frac{\pi}{2}, \frac{3\pi}{2}\right]$
Fore::Knee::ThContraction	$\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$
Hind::Knee::amplitude	$\left[0.0, \frac{\pi}{2}\right]$
Hind::Knee::ThExtension	$\left[\frac{\pi}{2}, \frac{3\pi}{2}\right]$
Hind::Knee::ThContraction	$\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$

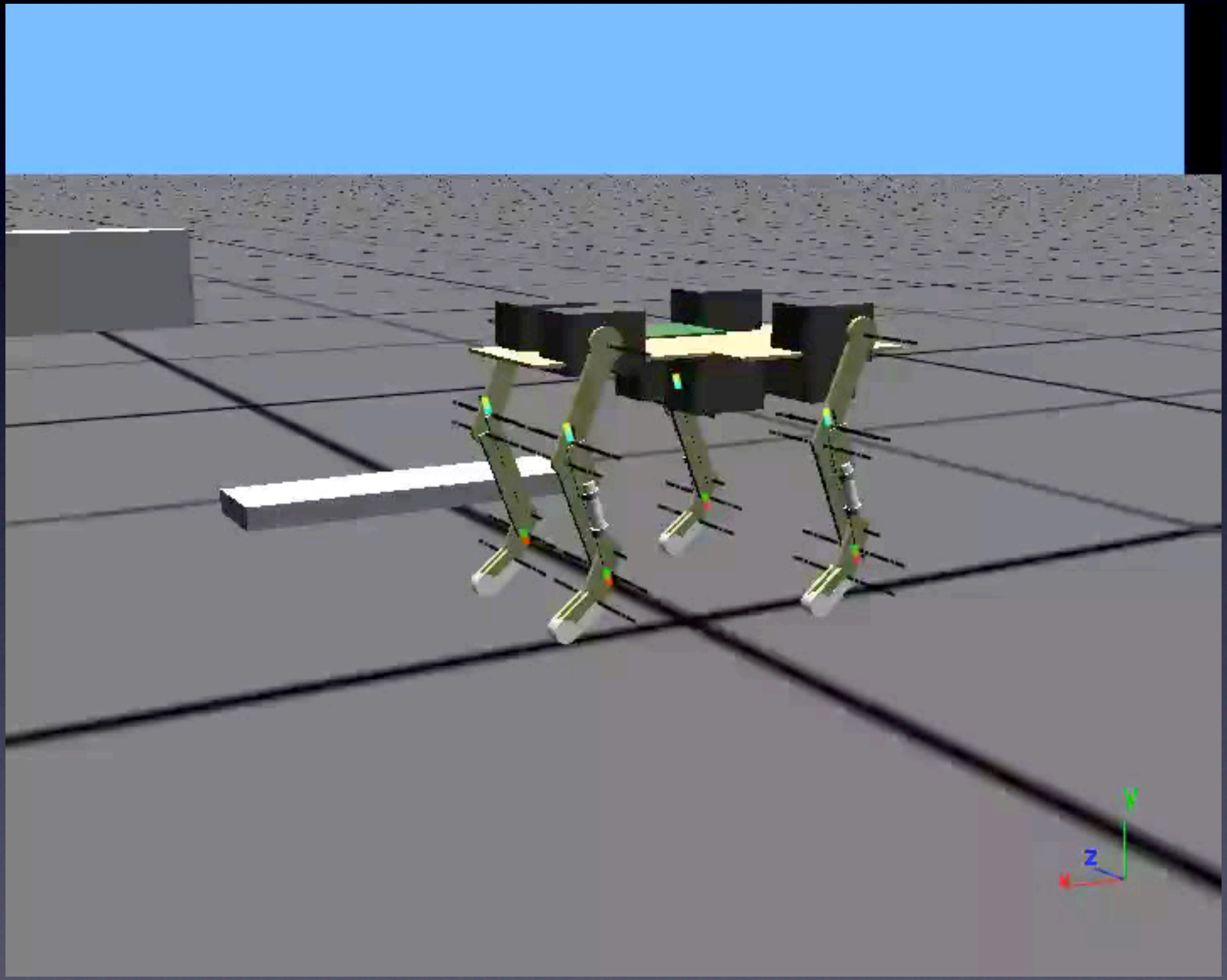
Optimization Definiton

- Using Particle Swarm Optimization
- Differentiate between hindlimb and forelimb parameter
- Takes highest boundary as possible

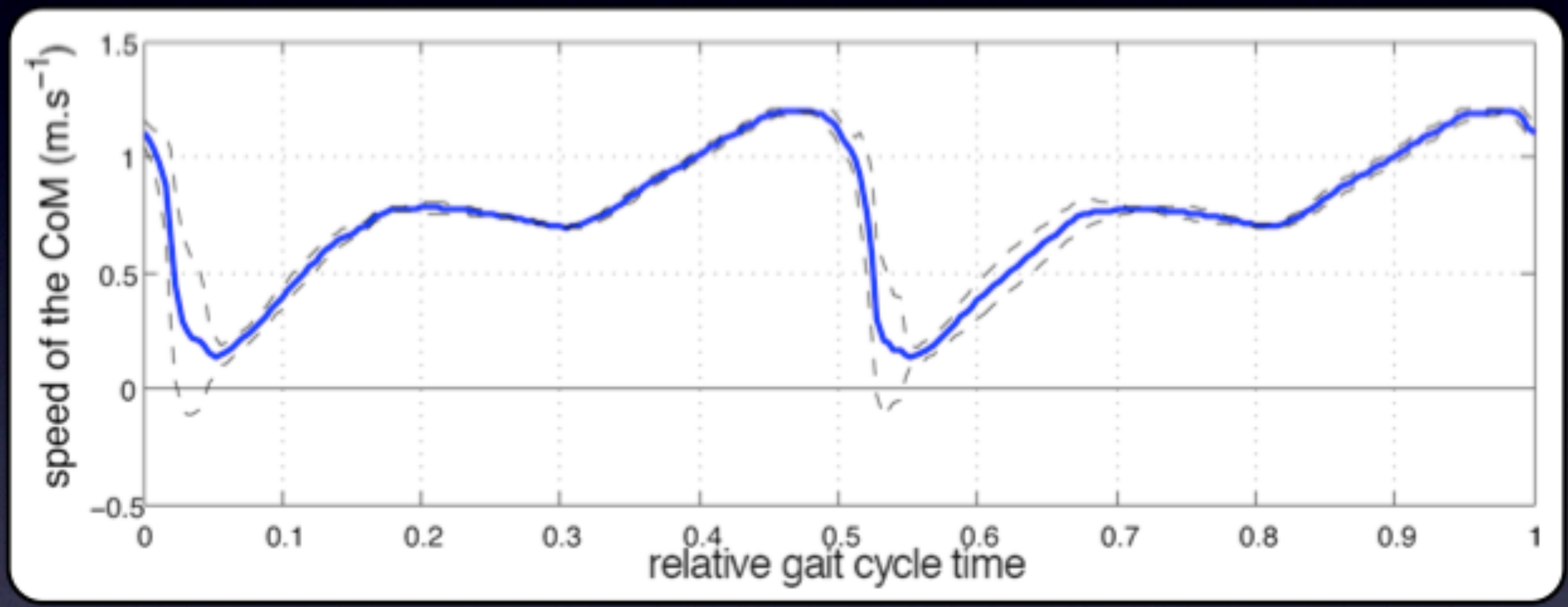
Name	Boundaries
Hip::duty	$[0.05, 0.95]$
Fore::Hip::amplitude	$[0.0, 2.0]$
Fore::Hip::offset	$[-1.3, 0.9]$
Fore::Hip::refraction	$\left[0.0, \frac{\pi}{2}\right]$
Hind::Hip::amplitude	$[0.0, 2.0]$
Hind::Hip::offset	$[-1.3, 0.9]$
Hind::Hip::refraction	$\left[0.0, \frac{\pi}{2}\right]$
Fore::Knee::amplitude	$\left[0.0, \frac{\pi}{2}\right]$
Fore::Knee::ThExtension	$\left[\frac{\pi}{2}, \frac{3\pi}{2}\right]$
Fore::Knee::ThContraction	$\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$
Hind::Knee::amplitude	$\left[0.0, \frac{\pi}{2}\right]$
Hind::Knee::ThExtension	$\left[\frac{\pi}{2}, \frac{3\pi}{2}\right]$
Hind::Knee::ThContraction	$\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$

First Learned gait

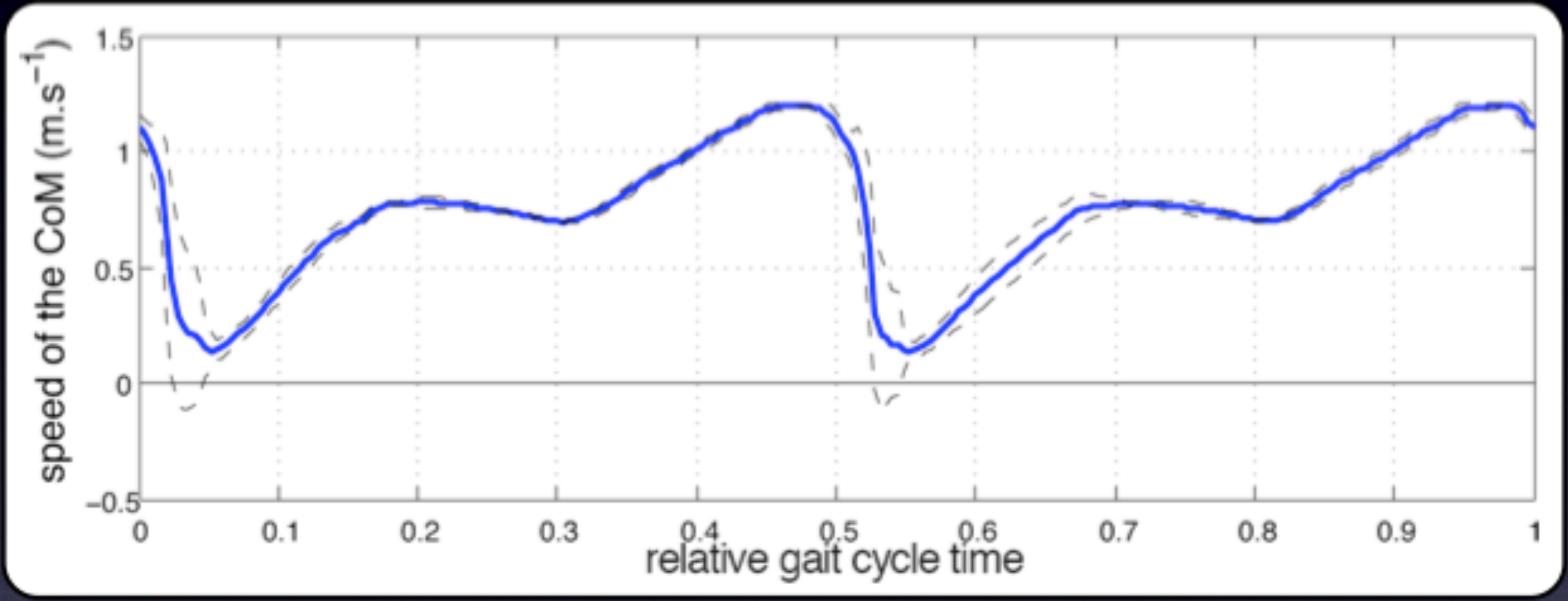
First Learned gait



Dynamical analysis

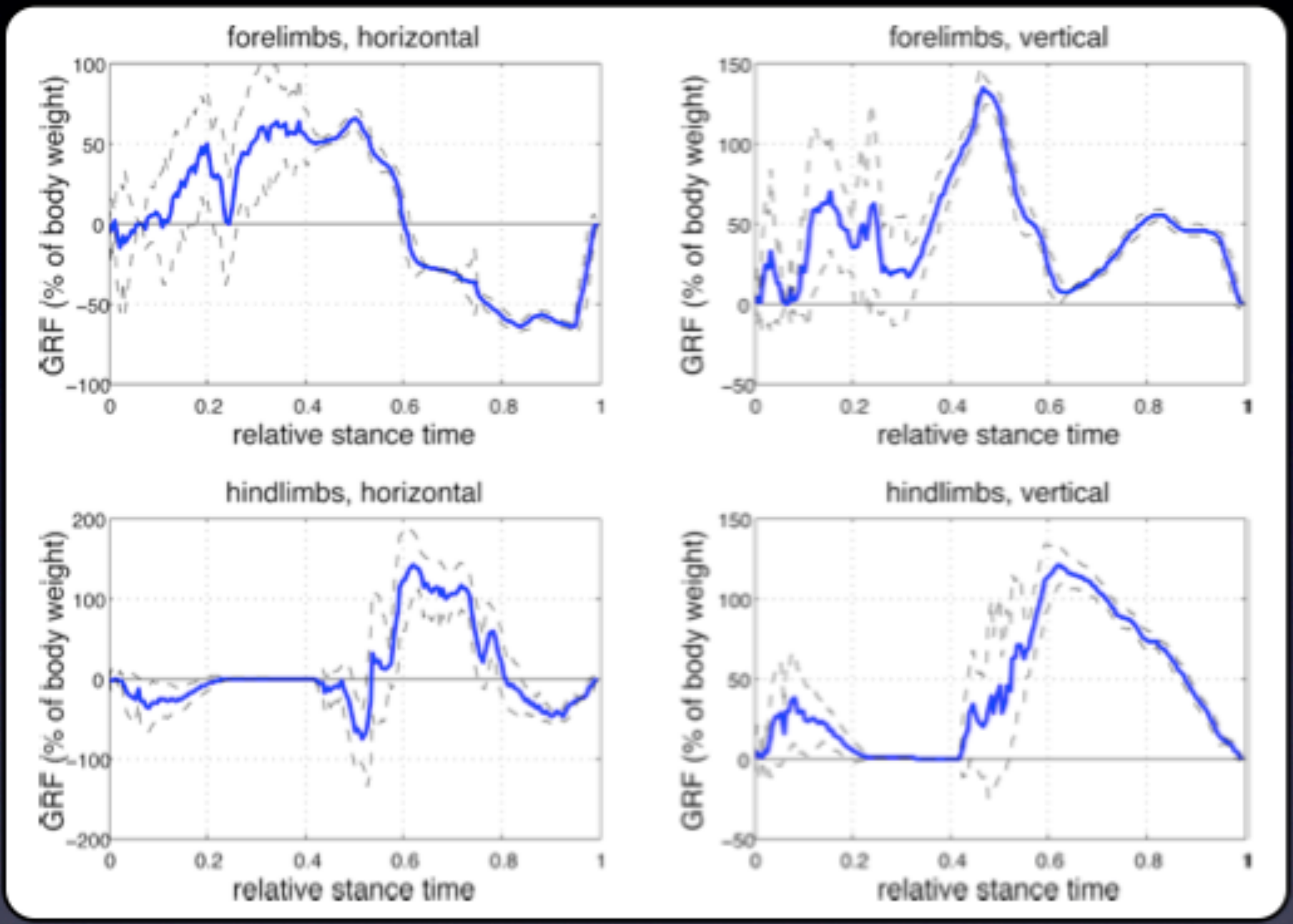


Dynamical analysis



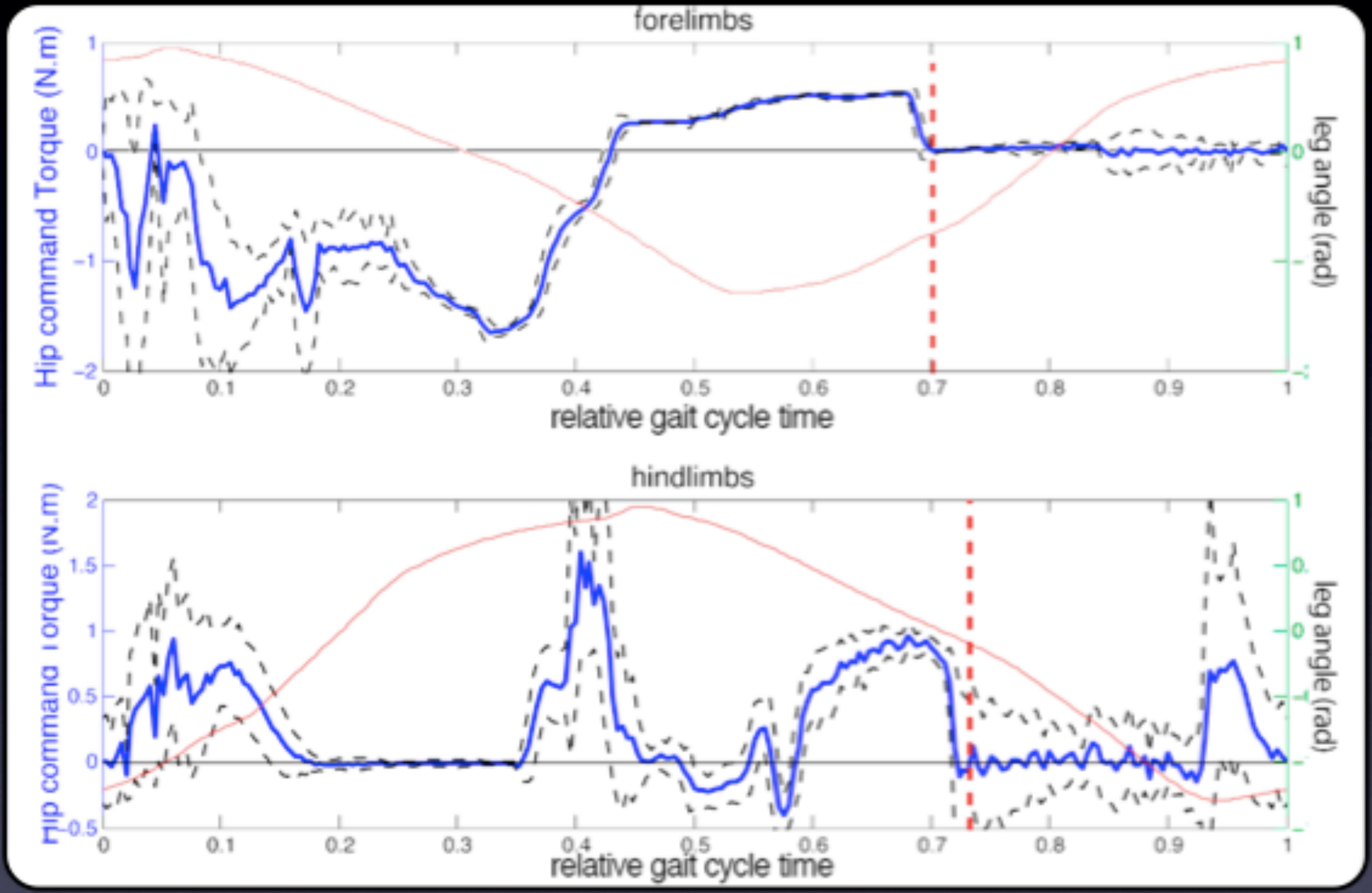
- "Breaked gait" : lose all it speed at touchdown

Dynamical analysis



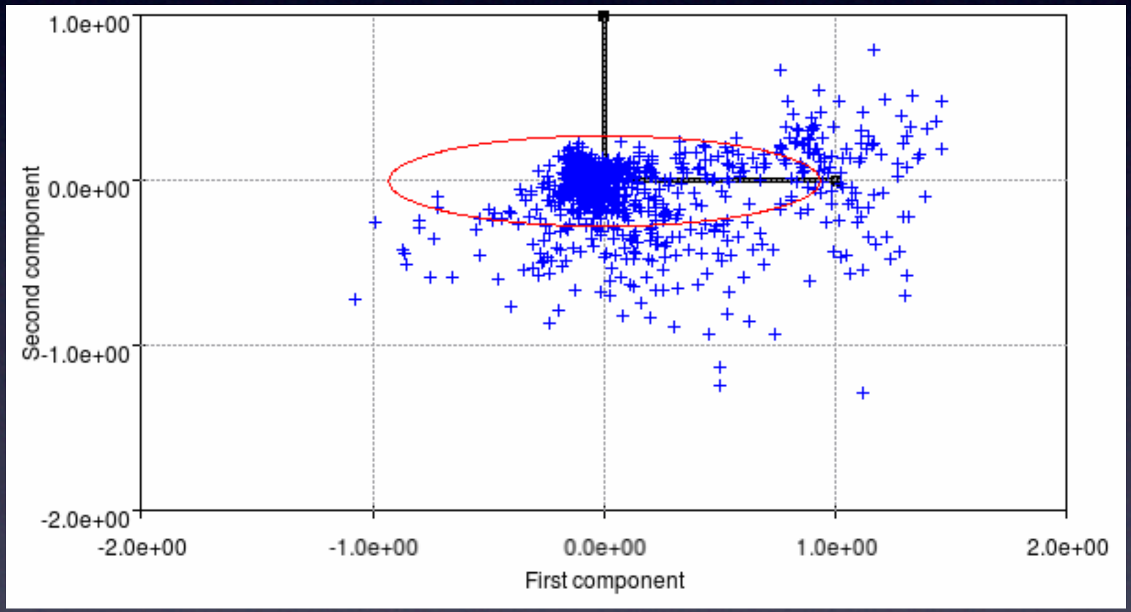
- “Breaked gait” : lose all it speed at touchdown
- Forelimb are propulsive, hindlimbs lake foot clearance

Dynamical analysis



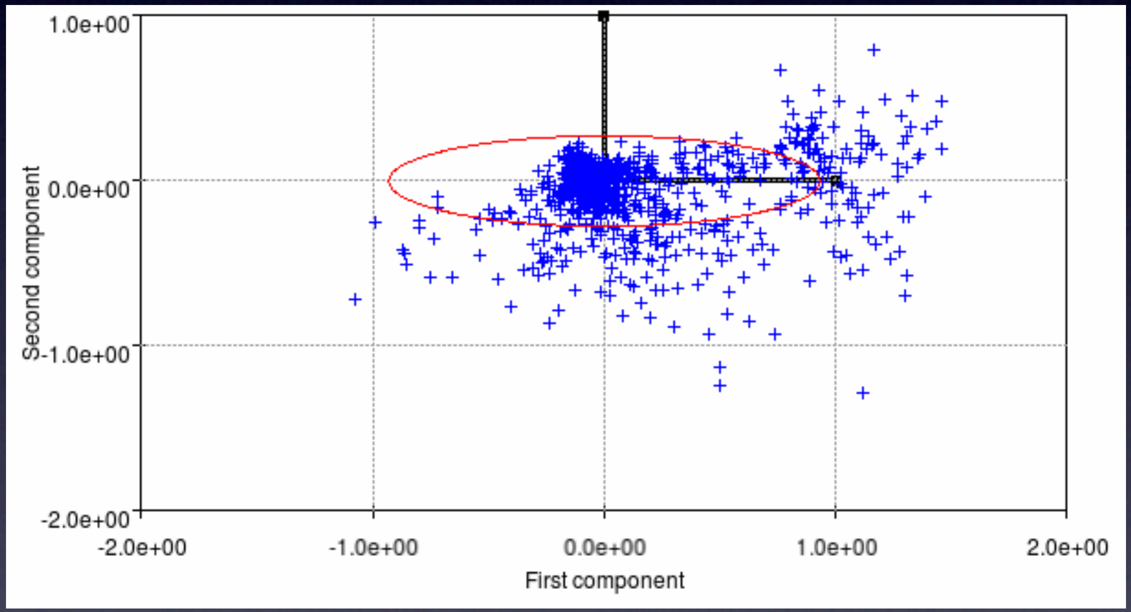
- "Breaked gait" : lose all it speed at touchdown
- Forelimb are propulsive, hindlimbs lake foot clearance
- Energetically unefficient : effector are taking energy of the system

Statistical method to find less influential parameters



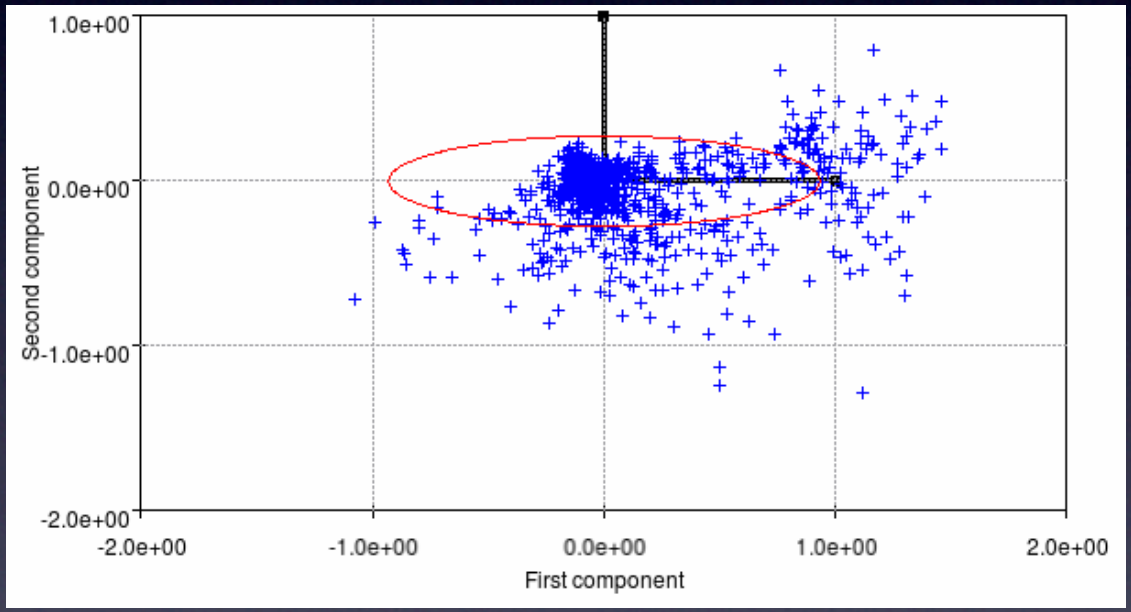
Statistical method to find less influential parameters

- Using PCA on the set of best particles over all iteration



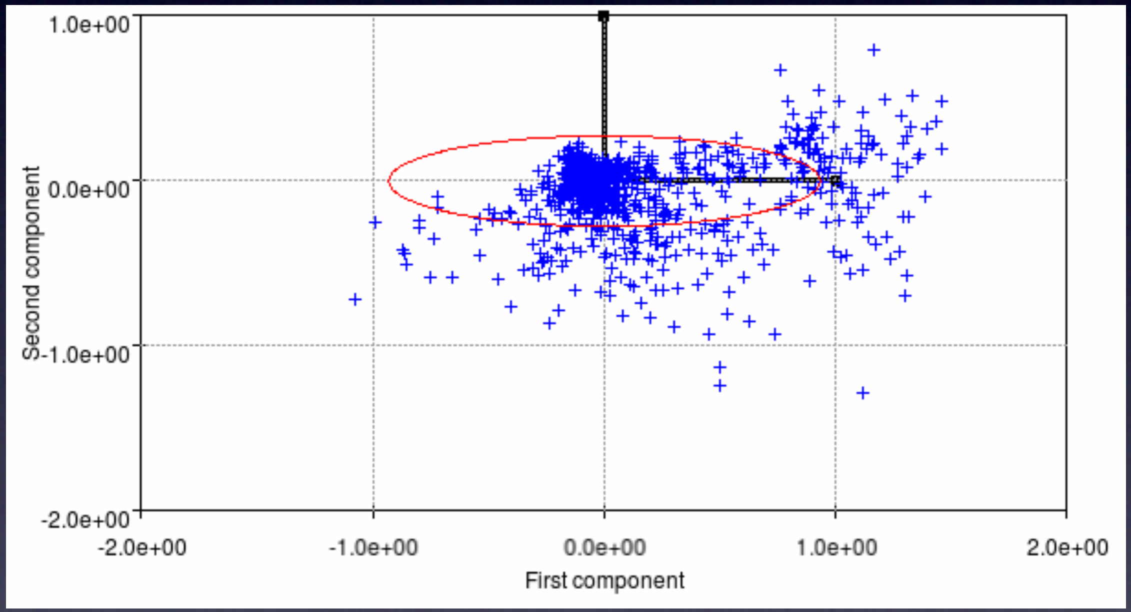
Statistical method to find less influential parameters

- Using PCA on the set of best particles over all iteration
- Principal Components will tell us if there is or not such parameters



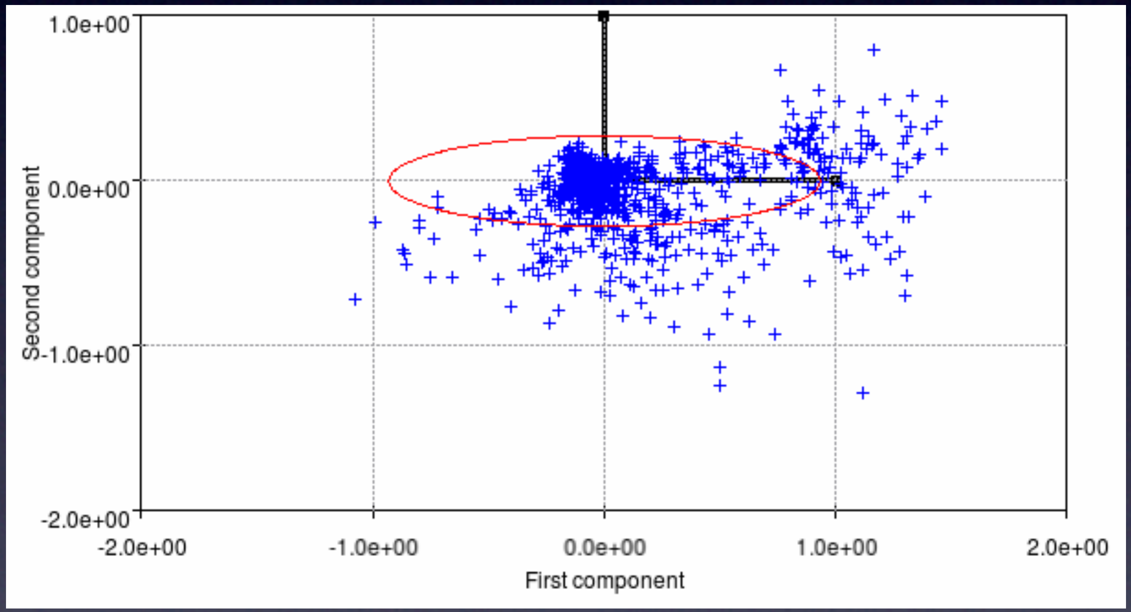
Statistical method to find less influential parameters

- Using PCA on the set of best particles over all iteration
- Principal Components will tell us if there is or not such parameters
- Caution : we may extracting the sctochastic characteristic of PSO !



Statistical method to find less influential parameters

- Using PCA on the set of best particles over all iteration
- Principal Components will tell us if there is or not such parameters
- Caution : we may extracting the sctochastic characteristic of PSO !
- For the gait, the less influential is the extension threshold



Insight for further improvement

Insight for further improvement

- Move the CoM from the hind to the front

Insight for further improvement

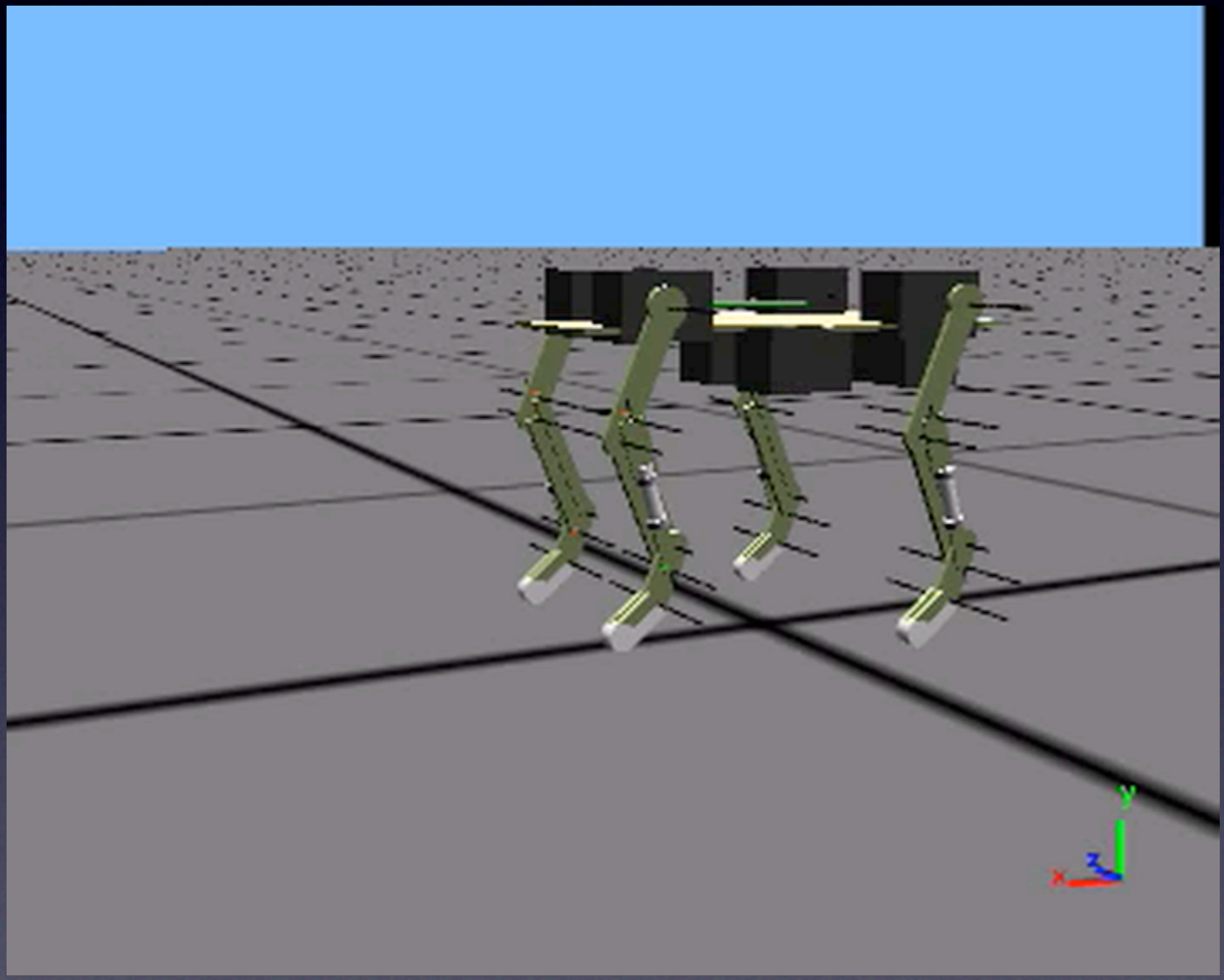
- Move the CoM from the hind to the front
- Increase stiffness and length of hindlimbs

Insight for further improvement

- Move the CoM from the hind to the front
- Increase stiffness and length of hindlimbs
- Add sensory feedback to ensure “clean” stance phase

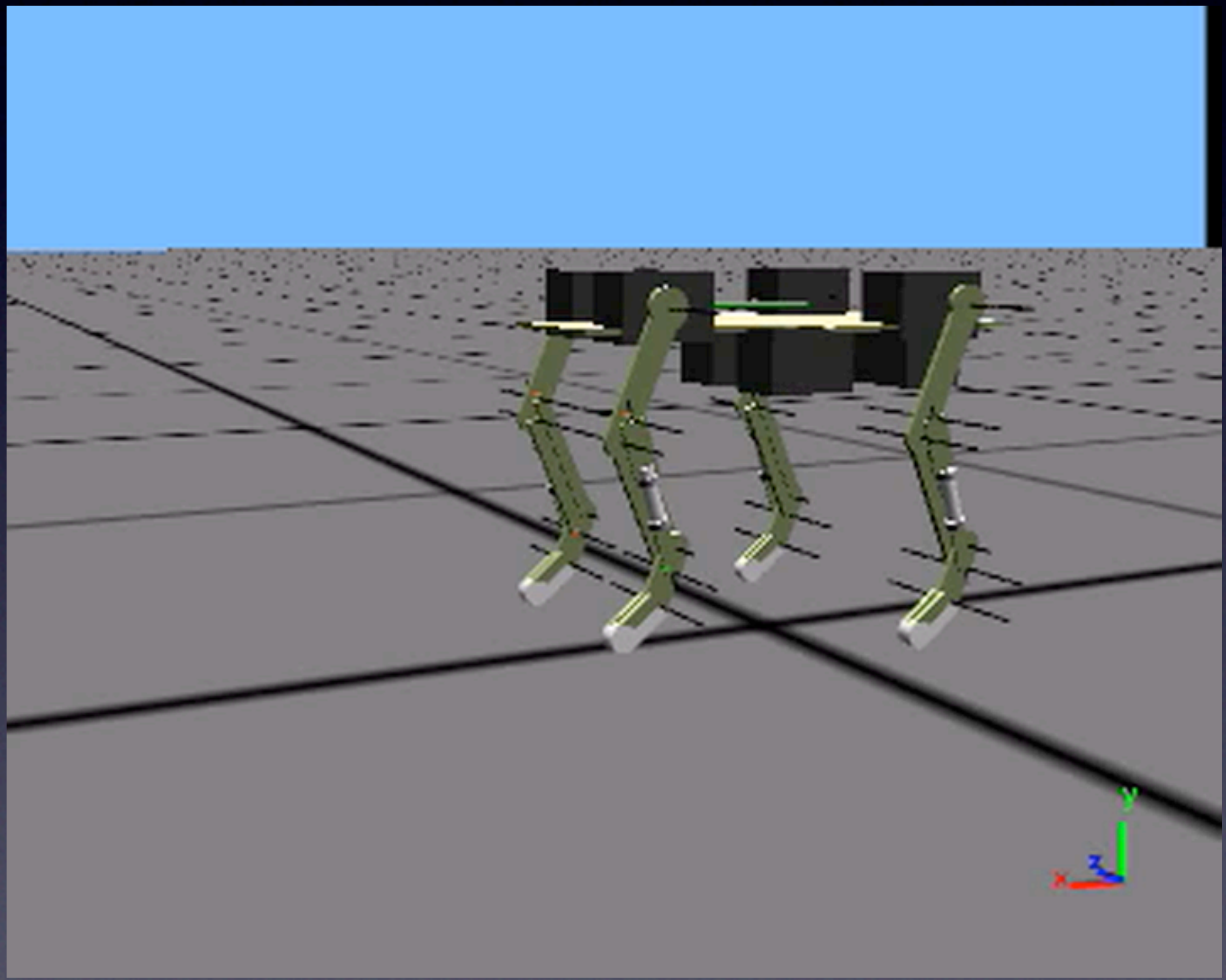
Learning Trot Gait with Sensory

Learning Trot Gait with Sensory



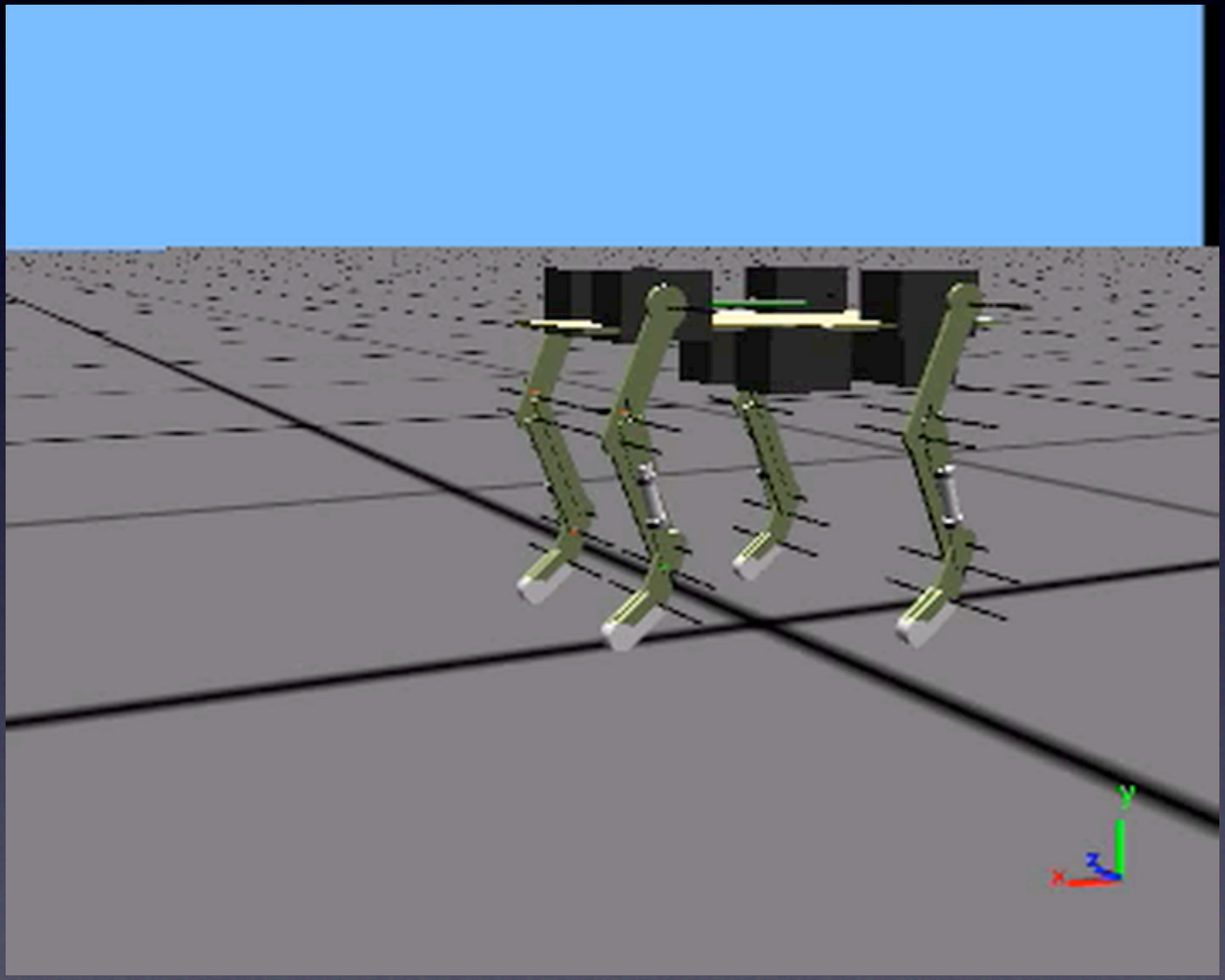
Learning Trot Gait with Sensory

- Added Sensory Feedback



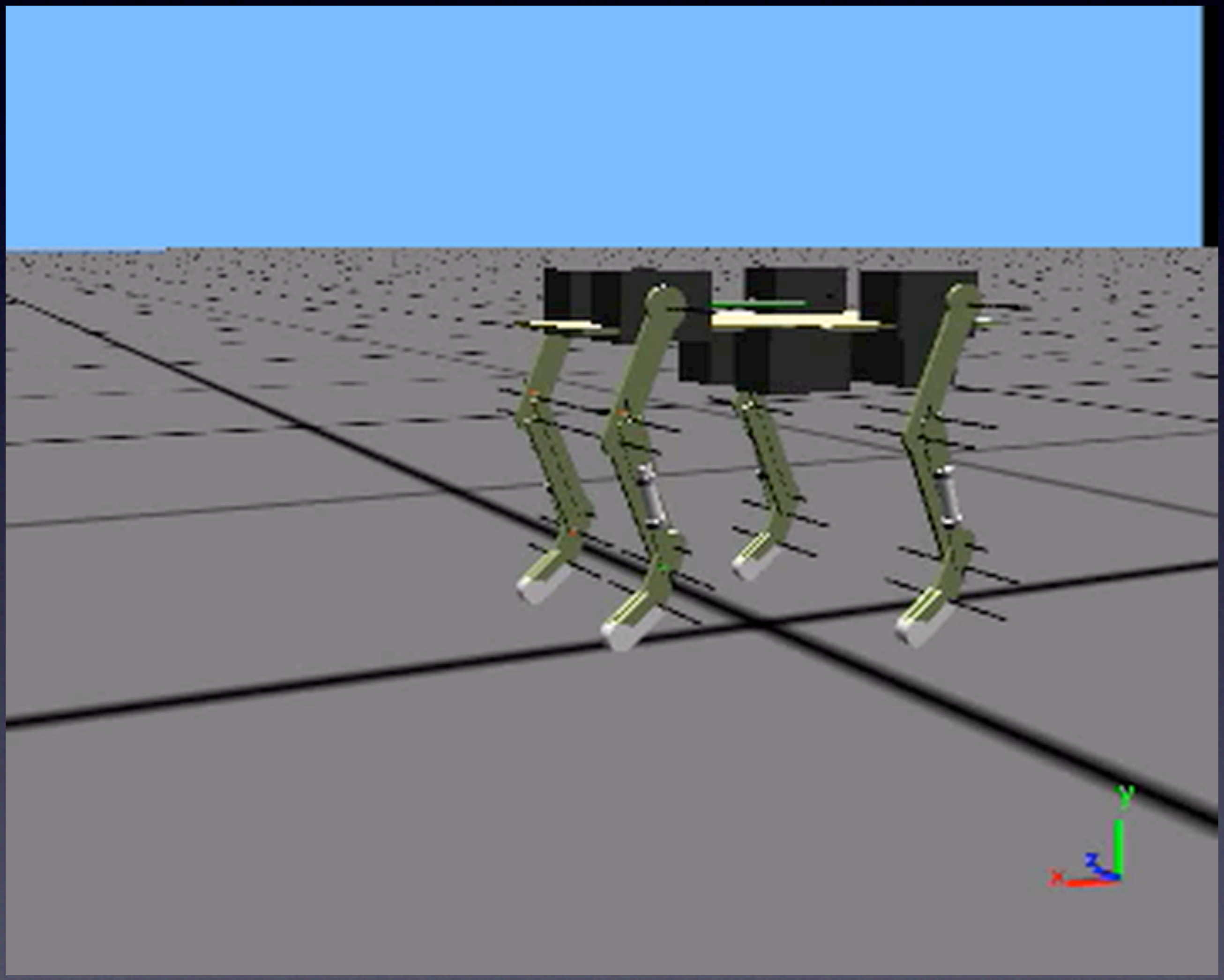
Learning Trot Gait with Sensory

- Added Sensory Feedback
- Optimized frequency

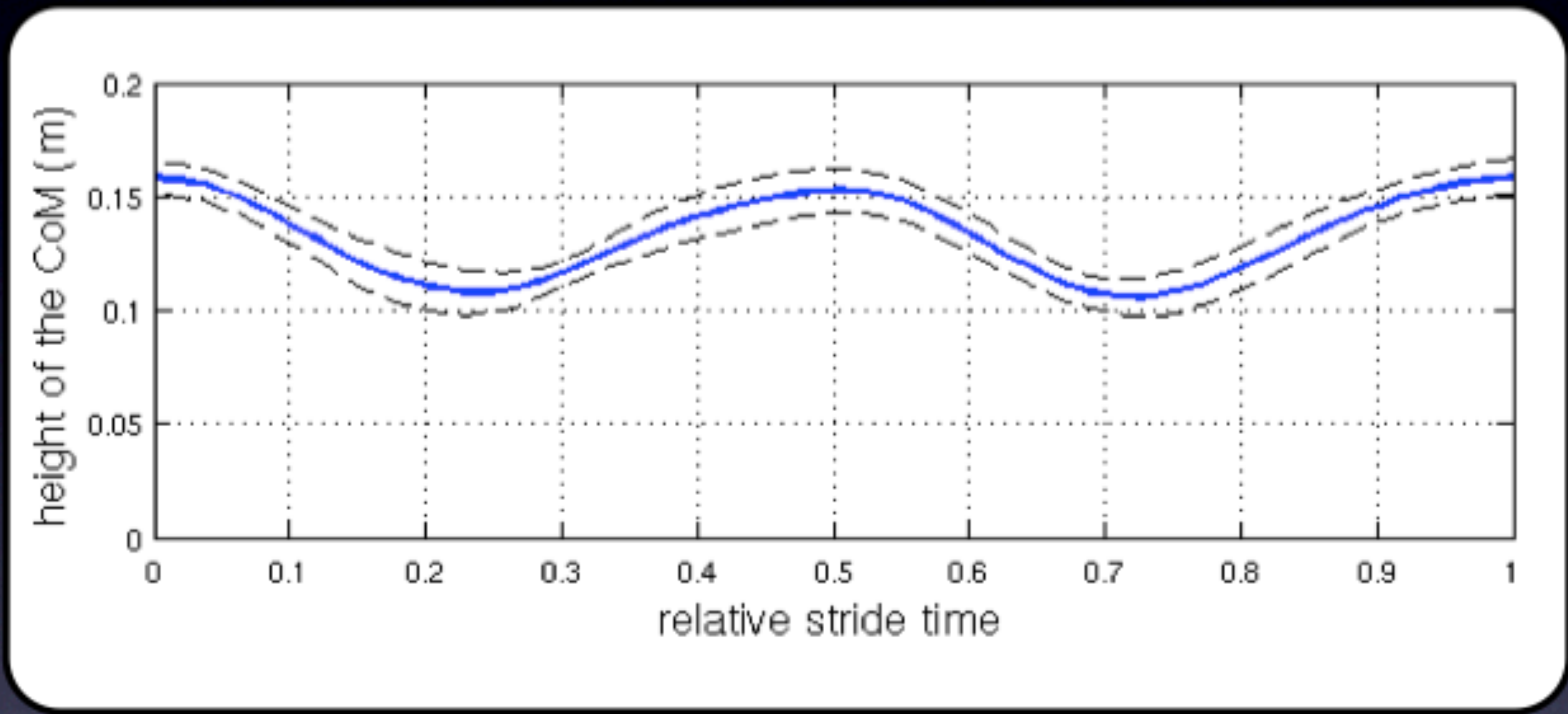


Learning Trot Gait with Sensory

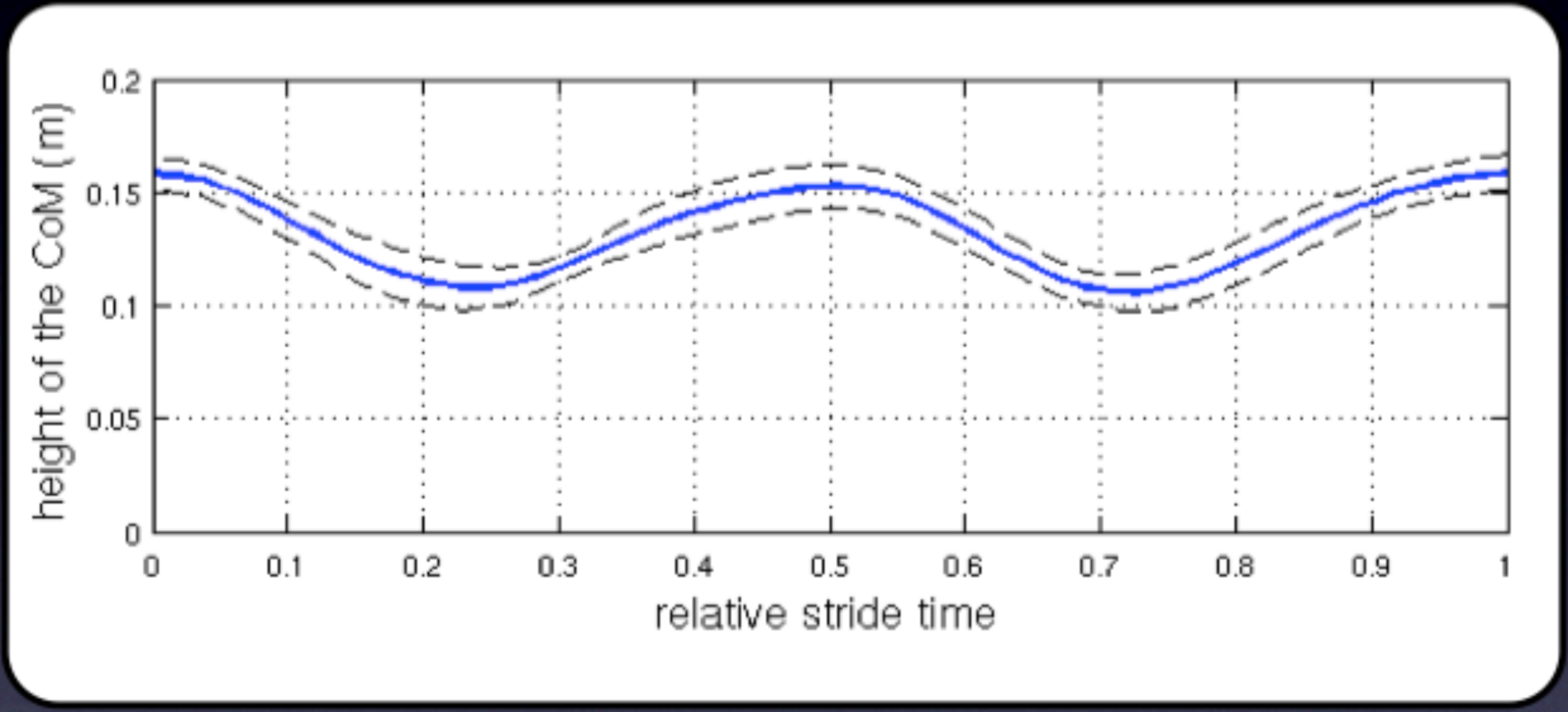
- Added Sensory Feedback
- Optimized frequency
- High instability of the gait in parameter space



Dynamical analysis

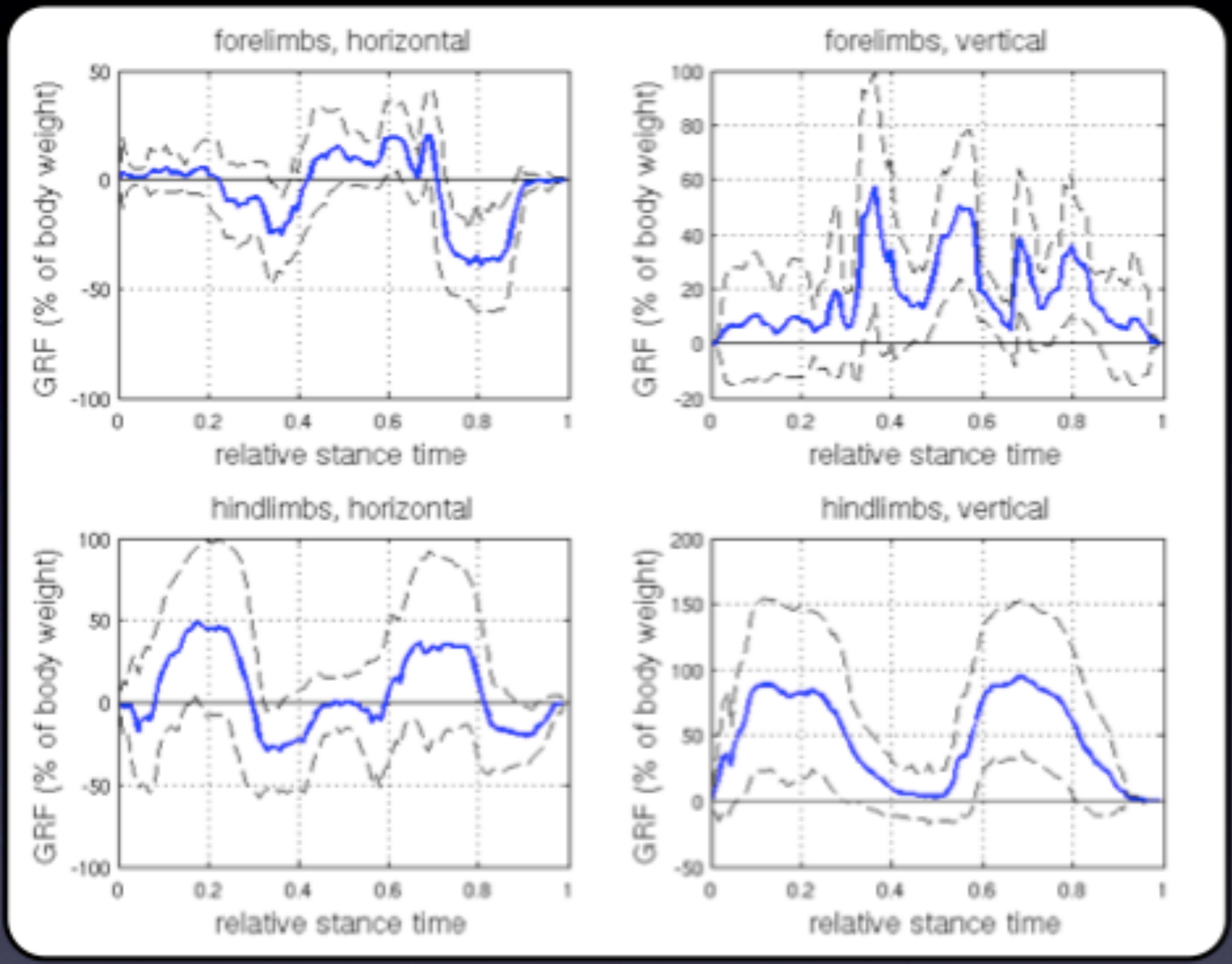


Dynamical analysis



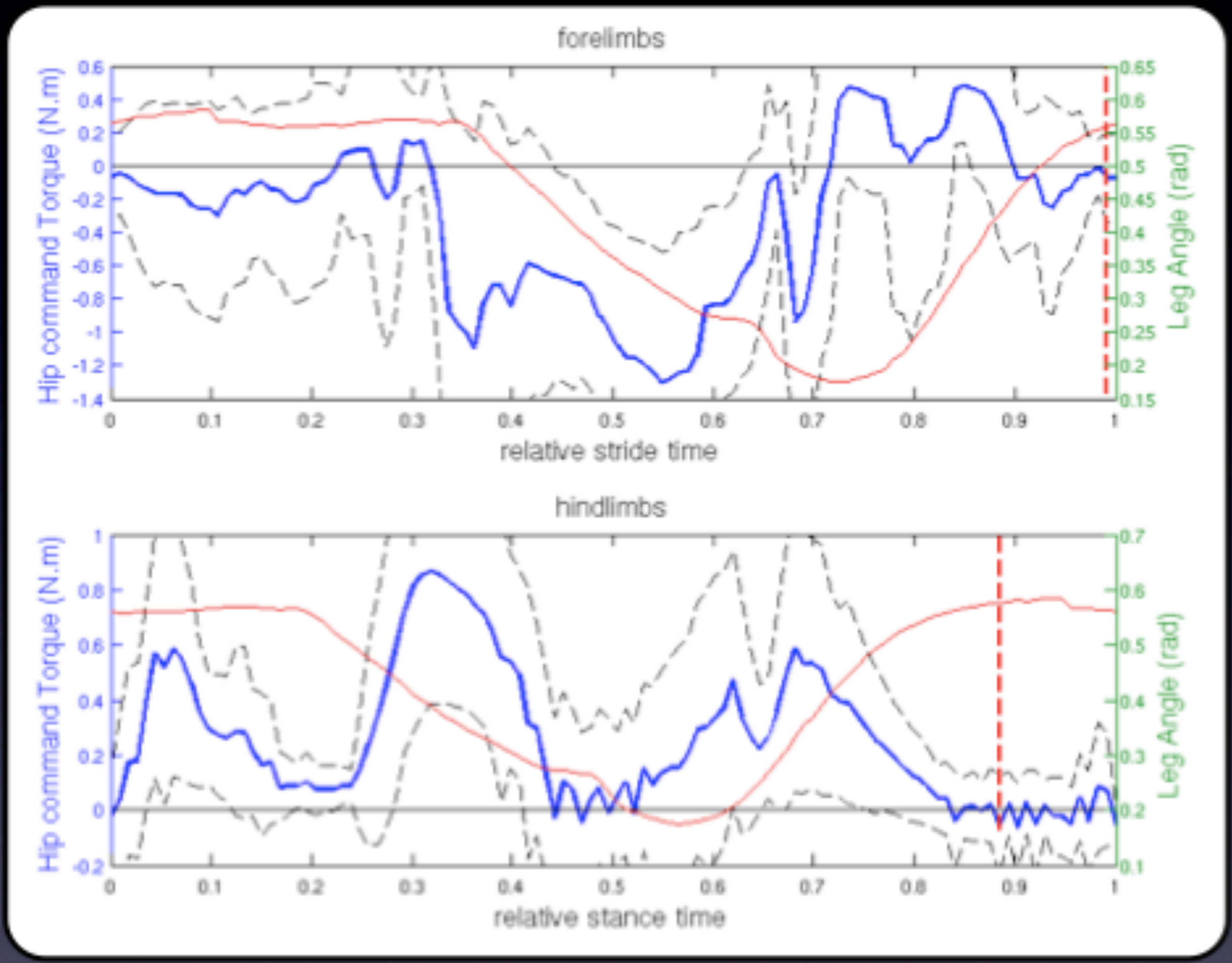
- CoM height is almost constant

Dynamical analysis



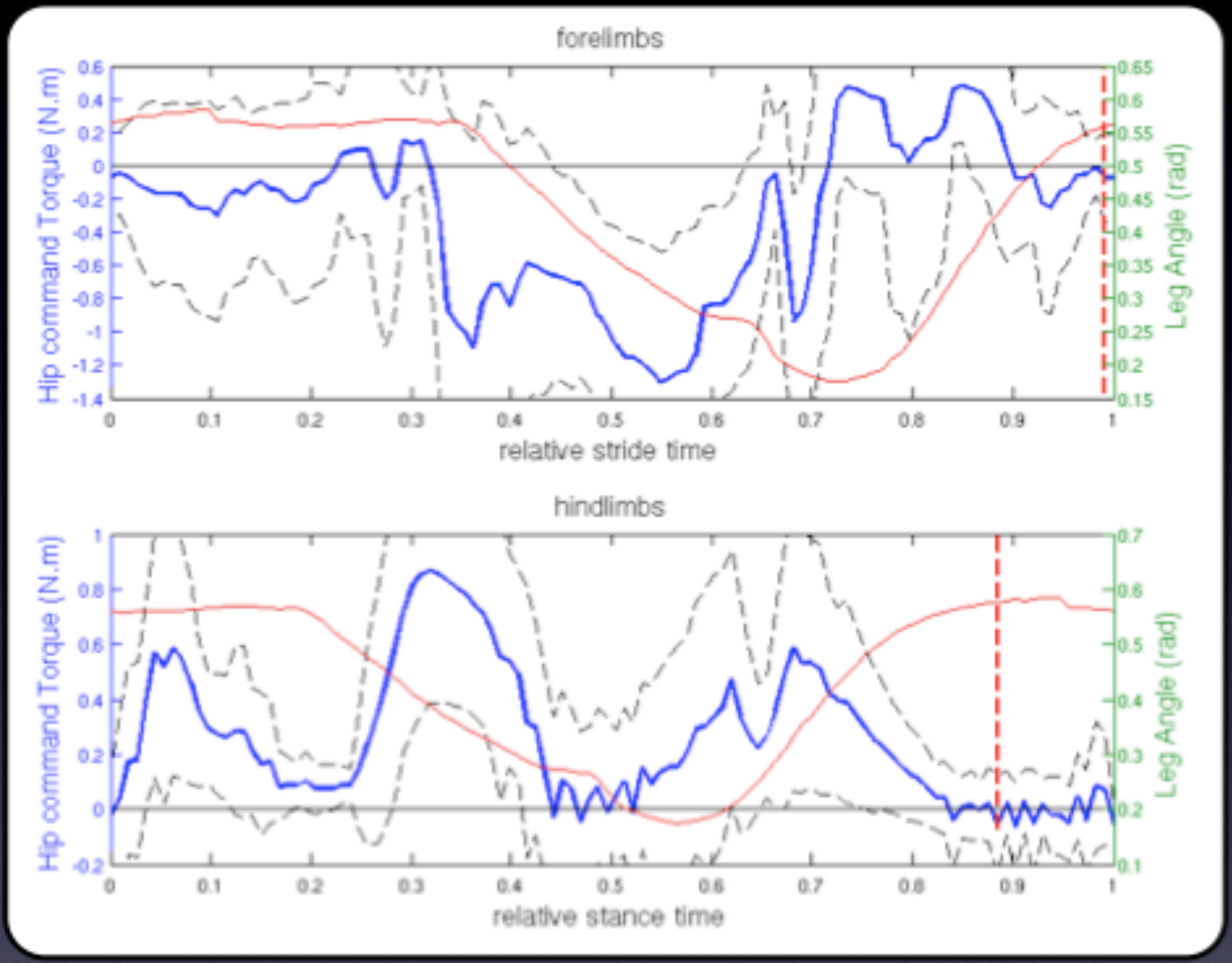
- CoM height is almost constant
- Forelimb less propulsive, "almost" clean stance phase

Dynamical analysis



- CoM height is almost constant
- Forelimb less propulsive, “almost” clean stance phase

Dynamical analysis



- CoM height is almost constant
- Forelimb less propulsive, “almost” clean stance phase
- Energetically efficient for forelimb at least.

Further Work

Further Work

- Test the gait to be stable for different duty ratio/frequency.

Further Work

- Test the gait to be stable for different duty ratio/ frequency.
- Mesure efficiency of the leg retraction principle by using stability criteria (APEX return map ....)

Further Work

- Test the gait to be stable for different duty ratio/ frequency.
- Mesure efficiency of the leg retraction principle by using stability criteria (APEX return map ....)
- Add new actuator, like a spinal coord, scapula joint ...

Questions ?