

# Development and implementation dynamic balance algorithms for bipedal robot locomotion

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# Outline

- Introduction and Motivation
- Problem Overview
- Related Work
- Theoretical Aspects of Bipedal Robots Control
- Implementation and Evaluation
- Future Work
- Summary

# Introduction and Motivation: the development of robotics in minds

Trends in robotics are near to be developed



Forbidden  
planet, 1956



RoboCop, 1987



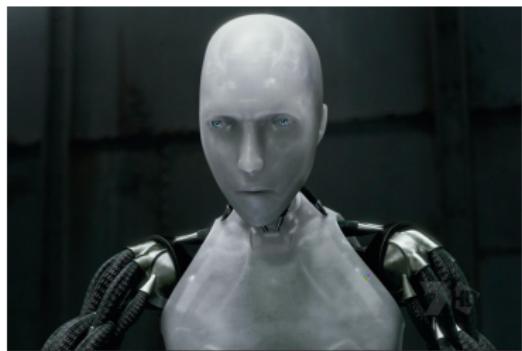
Bicentennial  
man, 1999

# Introduction and Motivation: the development of robotics in minds

Robotics, Cybernetics, Biomechatronics, AI are only several of prospectives that are required to take into account in bipedal robots development



Terminator, 1984



I, robot, 2004

# Introduction and Motivation: humanoid robots development



**ASIMO**  
<http://www.honda.co.jp/ASIMO/>  
<http://www.honda.co.jp/ASIMO/>

Evolution of Honda humanoids

# Introduction and Motivation

## What is a robot ?

- Mechanism with body structure resembles that of a human: head, torso, legs, arms, hands (Hirai et al. (1998))



Humanoid robot

# Introduction and Motivation

## Why humanoids ?

- Ability to work directly in the same human environment without any modification
- General-purpose workers
- Social integration
- Work with same tools as humans

# Introduction and Motivation

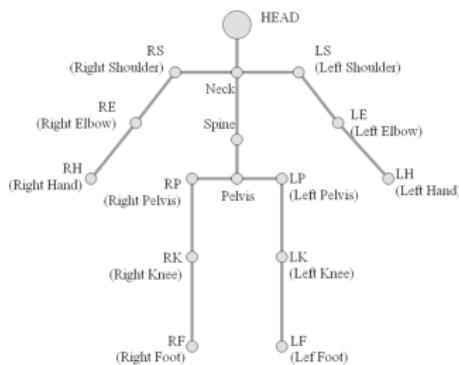
## Humanoids Advantages and Disadvantages

- (+) Universal environment
- (+) Natural, human-like
- (+) Uneven terrains
- (-) Difficult locomotion
- (-) Complex design
- (-) Low speed
- (-) Complex control
- (?) Special tasks cannot be performed by general robots as good as by devices that were designed for this proper task

# Problem Overview

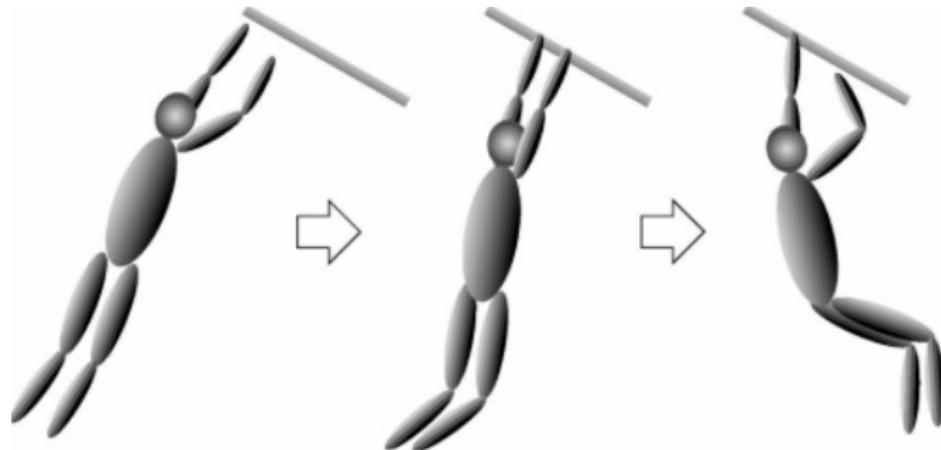
## Bipedal locomotion difficulties

- Humanoids are underactuated due to inertia frame
- Difficult to solve Inverse Kinematics
- Several kinematic chains
- Requires the robot to plan motions



Human represented as a set of kinematic chains, (Seo et al. (2011))

## Problem Overview



Human structure changing (Nakamura and Yamane (2000))

## Bipedal locomotion control approaches

- Analytical approach (ZMP based and others)
- Central Pattern Generator (CPG) approach
- Neural Networks approach
- Hidden Markov Model approach
- Rule based approach

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# Related work: Analytical approach

## Steps required for bipedal locomotion

- Apply stability constraints
- Design a gait algorithm
- Solve remaining Degrees of Freedom

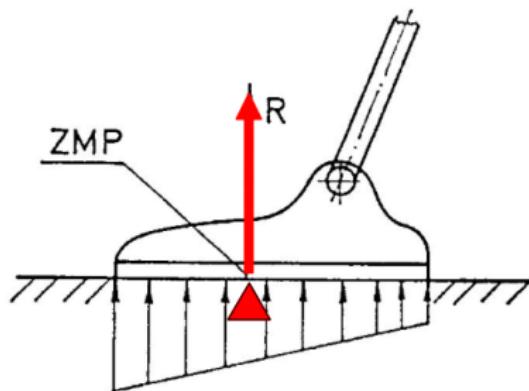
## Stability measures

- Zero Moment Point (ZMP)
- Foot Rotation Indicator (FRI)

## Related work: Analytical approach

### ZMP

- The distributed floor reaction force can be replaced by a single force  $R$  acts on Zero Moment Point



Zero Moment Point (ZMP) (Vukobratović and Borovac (2004))

# Related work: Central Pattern Generator Approach

## Human walking process

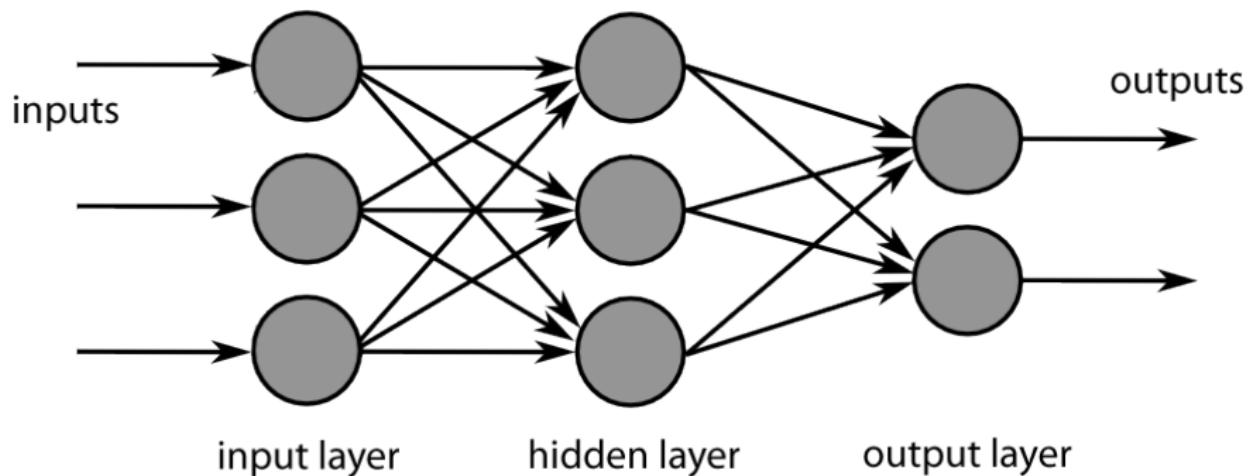
- Rhythm generating
- Control and adaptation mechanism

## CPG principle

- Biological CPGs are made from pairs of mutually inhibiting neurons
- Pairs of mutually inhibiting neurons are described by systems of differential equations
- CPG is a neural network working without input

## Related work: Neural Networks Approach

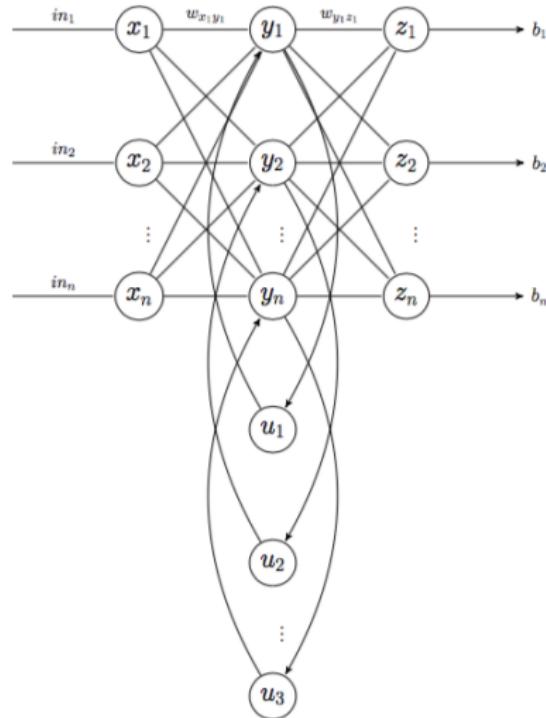
### Feed-Forward Networks



Feed Forward Network (Kim et al. (2012))

# Related work: Neural Networks Approach

## Recurrent networks



Elman Recurrent Network

# Related work: Hidden Markov Model Approach

## HMM for bipedal locomotion algorithm

- A correspondence between the control signal and controller input
- The control signal depends only on a finite number of previous input signals
- Define a set of patterns
- Set of input signals is mapped to the set of possible control signals
- Train the model by the data describing control signals
- Collect a set of trained models

# Related work: Rule Based Approach

## Rule Based Approach principle

- Divide the set of all possible system configurations into the clusters
- For each cluster assign the control function
- During the work control function will be chosen according to the current robot configuration

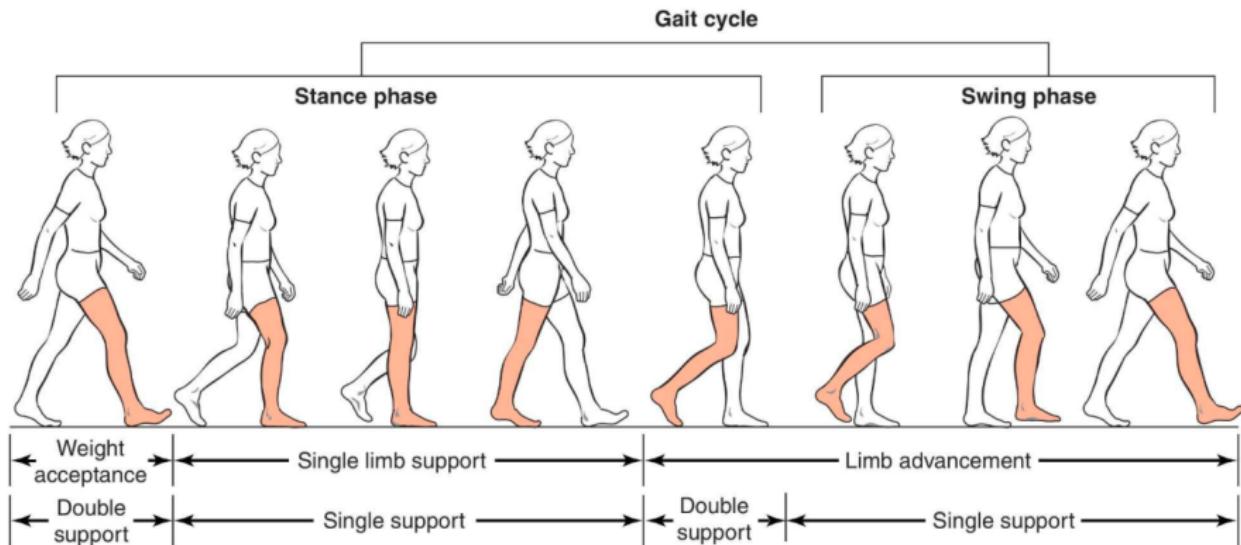
# Related work: Rule Based Approach

## Rule Based Approach principle

- Current configuration defines the possible control function
- Fuzzy logic controller is a perspective approach for solving dynamical stability problem
- Fuzzy logic controller divide all the configuration space into the subspaces
- For each subspace control function is defined in an optimal way

# Theoretical Aspects of Bipedal Robots Control

Locomotion is a periodic gait cycle.

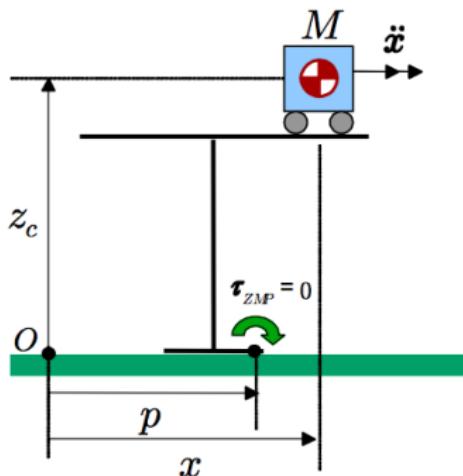


Gait cycle decomposition (Hill (2015))

# Theoretical Aspects of Bipedal Robots Control

## Cart table model

- (+) Easy to understand
- (-) Not precise



Cart table model (Kajita et al. (2003))

# Theoretical Aspects of Bipedal Robots Control: cart table model

## Cart table model

- M is cart mass
- x is cart trajectory
- $\ddot{x}$  is cart acceleration
- p is ZMP coordinate
- $Z_c$  is height of cart CoM
- $\tau_{ZMP}$  is rotational moment in ZMP
- Cart table dynamics:

$$P = x - \frac{Z_c}{g} \ddot{x} \quad (1)$$

# Theoretical Aspects of Bipedal Robots Control: cart table model

## Proper dynamics of cart table model

- 

$$\frac{d}{dt} \begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u \quad (2)$$

- 

$$p = \begin{bmatrix} 1 & 0 & -\frac{Z_c}{g} \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix} \quad (3)$$

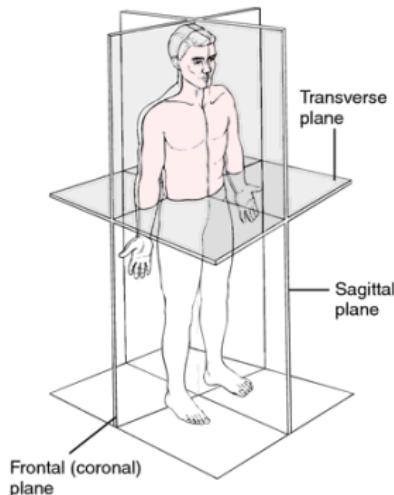
- $u$  is the jerk

$$u = \frac{d^3x}{dt^3} \quad (4)$$

# Theoretical Aspects of Bipedal Robots Control

## Human planes interesting for locomotion

- Sagittal plane
- Frontal plane

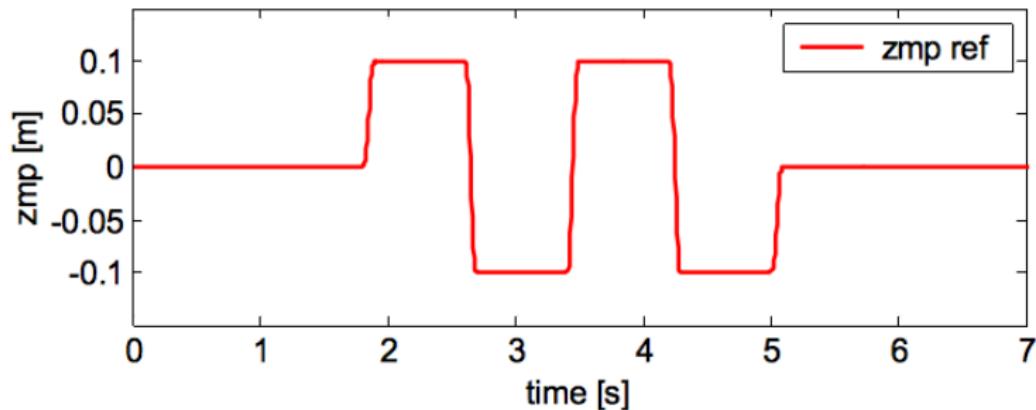


Human planes (Stedman (2015))

# Theoretical Aspects of Bipedal Robots Control

## Control principle

- Find ZMP pattern that corresponds to desired robot locomotion direction
- Calculate the cart trajectory to realize the given ZMP pattern
- Apply correction to robot in order to follow pattern

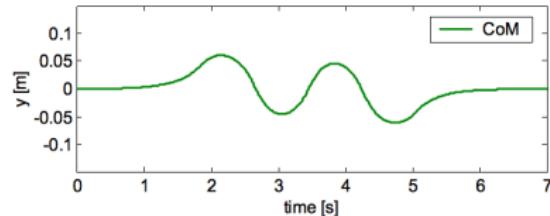
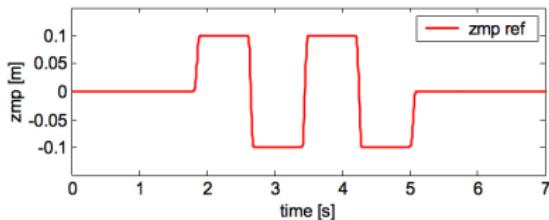


ZMP desired trajectory in frontal plane (Kajita et al. (2003))

# Theoretical Aspects of Bipedal Robots Control

## Control principle

- Find ZMP pattern that corresponds to wanted robot locomotion direction
- Calculate the cart trajectory to realize the given ZMP pattern
- Apply correction to robot in order to follow pattern

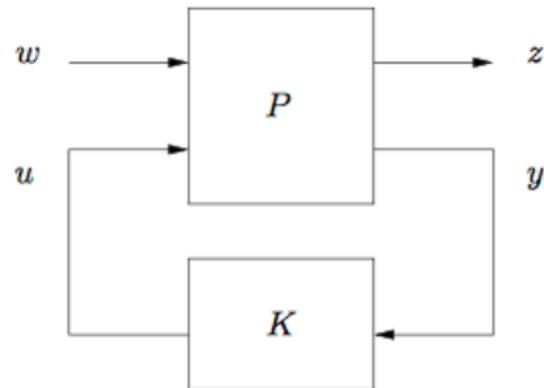


Inverse control principle (Kajita et al. (2003))

# Theoretical Aspects of Bipedal Robots Control

## Optimal Control

- State space model
- Transfer function
- Transfer function measures



Generalized regulator (Hazell (2008))

# Theoretical Aspects of Bipedal Robots Control: Optimal Control

## Optimal Control

- State space model

$$\begin{aligned}x(k+1) &= Ax(k) + Bu(k) \\y(k) &= Cx(k) + Du(k)\end{aligned}\tag{5}$$

A, B, C, D are parameters matrices. x is a input vector, y is output vector.

- Transfer function

$$G(Z) = C(ZI - A)^{-1}B + D\tag{6}$$

Where Z is Z transform variable

# Theoretical Aspects of Bipedal Robots Control: Optimal Control

## Optimal Control

- Transfer function measures

$$\|G(Z)\|_2 = \text{Trace}\{B^T X B + D^T D\} \quad (7)$$

- X should satisfy:

$$X = A^T X A + C^T C \quad (8)$$

- Physical meaning is a gain in power from input to output, assuming that the input signal is white noise



White noise realisation (Manchester et al. (2011))

# Theoretical Aspects of Bipedal Robots Control: Optimal Control

## Optimal Control

- Transfer function measures

$$\|G(Z)\|_{\infty} = \sup_{\omega} \frac{\|z\|_2}{\|\omega\|_2} \quad (9)$$

•

$$z = G\omega \quad (10)$$

- $\omega$  is assumed to be a realization of a unit power, Gaussian, white noise process and  $z$  is the real values vector of input
- Physical meaning is a maximum possible gain in power from input to output, assuming that the input signal is white noise

# Theoretical Aspects of Bipedal Robots Control: Preview Control

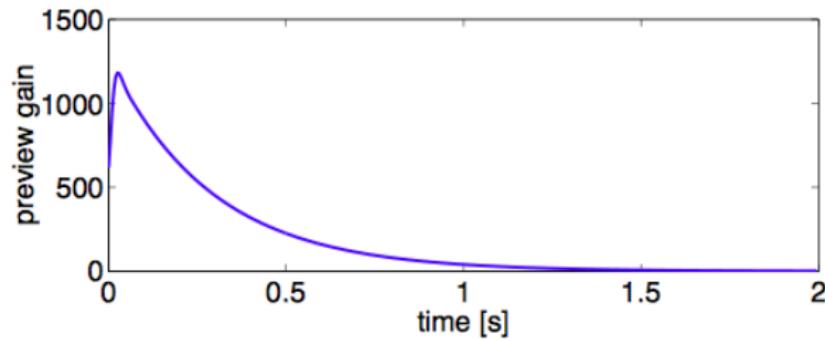
## Preview Control

- Look forward for N discrete steps
- Predict the desirable value of controlled signal
- (Katayama et al. (1985)) proved the theorem that optimal control signal has the followong form:

$$u(k) = -G_I \sum_{i=0}^k e(i) - G_x x(k) - \sum_{l=1}^N G_d(l) y_d(k+l) \quad (11)$$

# Theoretical Aspects of Bipedal Robots Control: Preview Control

It makes sense to find critical number of important future steps.



Preview Gain dependency from the time (Kajita et al. (2003))

# Implementation and Evaluation

## What was done?

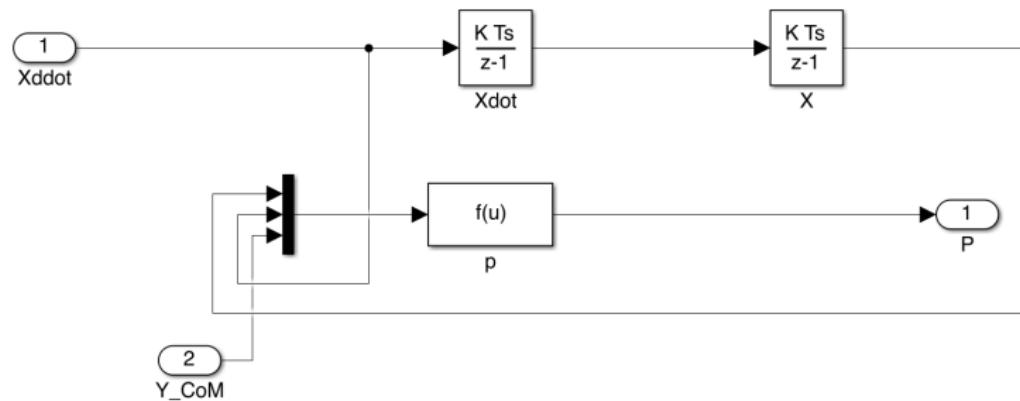
- Implementation of cart table model
- Implementation of PID controlled cart table model
- Implementation of preview controlled cart table model
- Comparison of preview and PID control result
- Preview control was applied to robot model

# Implementation and Evaluation: Cart table model

## Cart table model

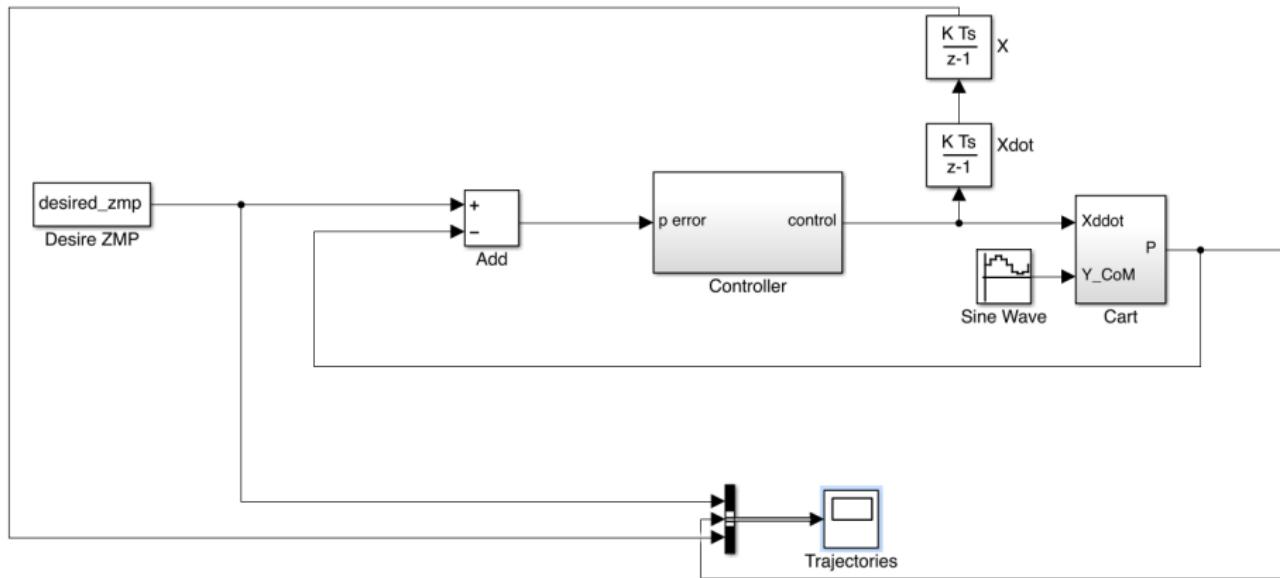
- Can be described by the following equation:

$$P = x - \frac{Z_c}{g} \ddot{x} \quad (12)$$



Cart table model in simulink environment

# Implementation and Evaluation: PID controlled cart table model

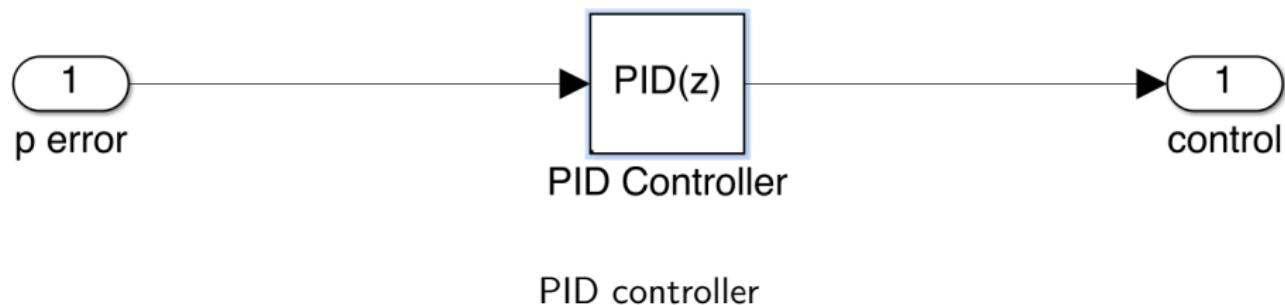


PID controlled cart table

# Implementation and Evaluation: PID controller

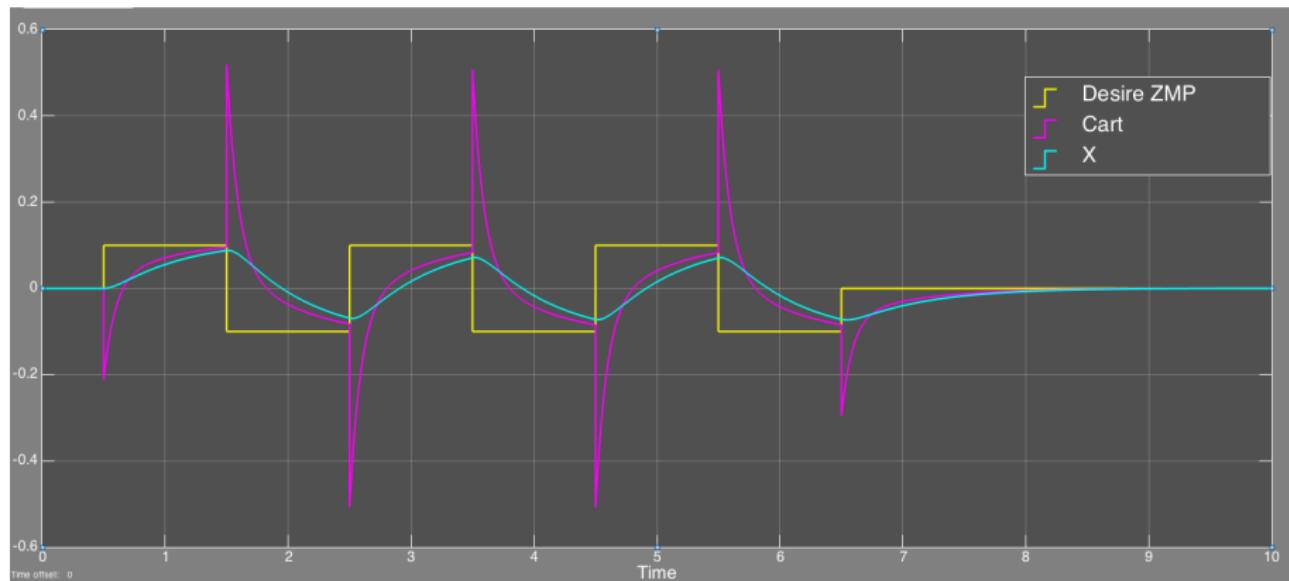
## PID controller

- PID controller is defined by its coefficients
- Coefficients can be adjusted by several algorithms: response analysis, transfer function analysis
- In this work matlab proprietary algorithm was used



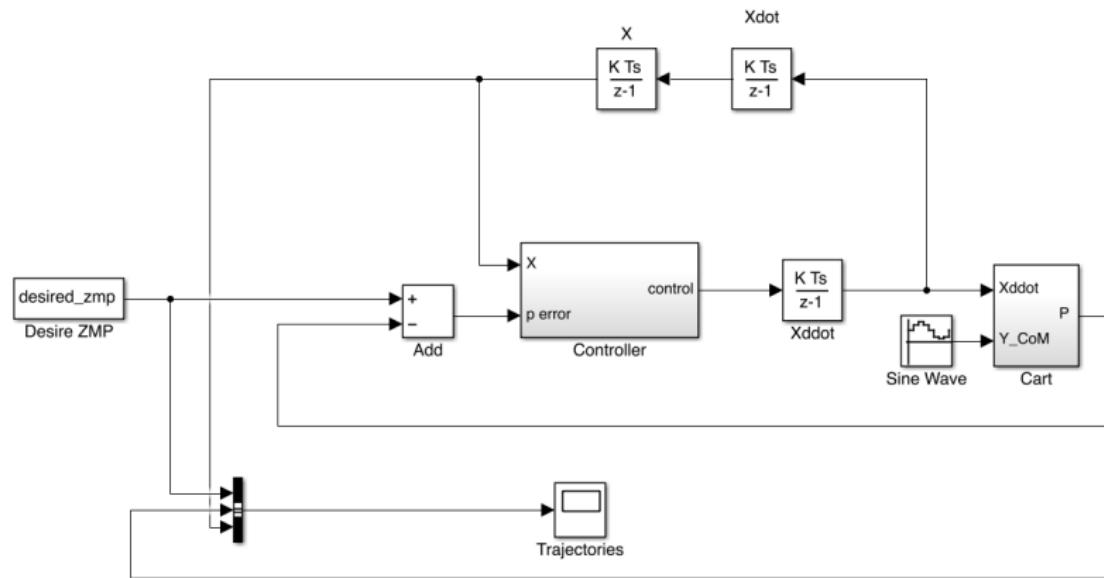
# Implementation and Evaluation: PID controller

The results of PID control show that it cannot be applied for such unstable system as cart on table



PID controlled cart table model results

# Implementation and Evaluation: Preview controlled cart table model

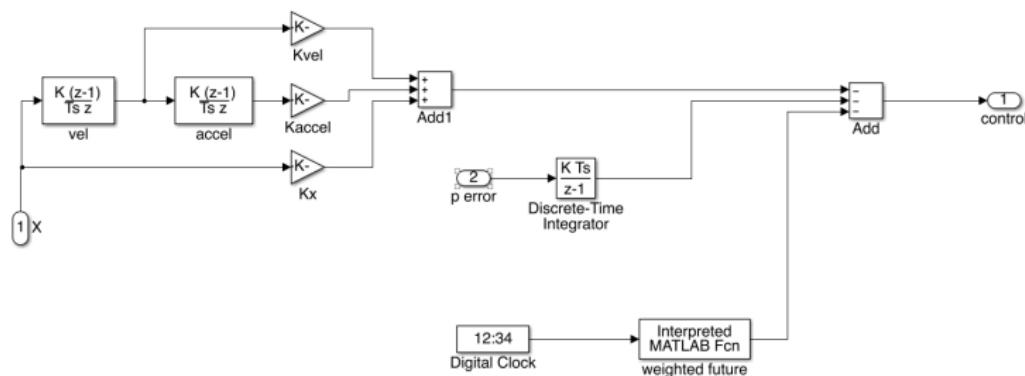


Preview controlled cart table

# Implementation and Evaluation: Preview controller

## Preview controller

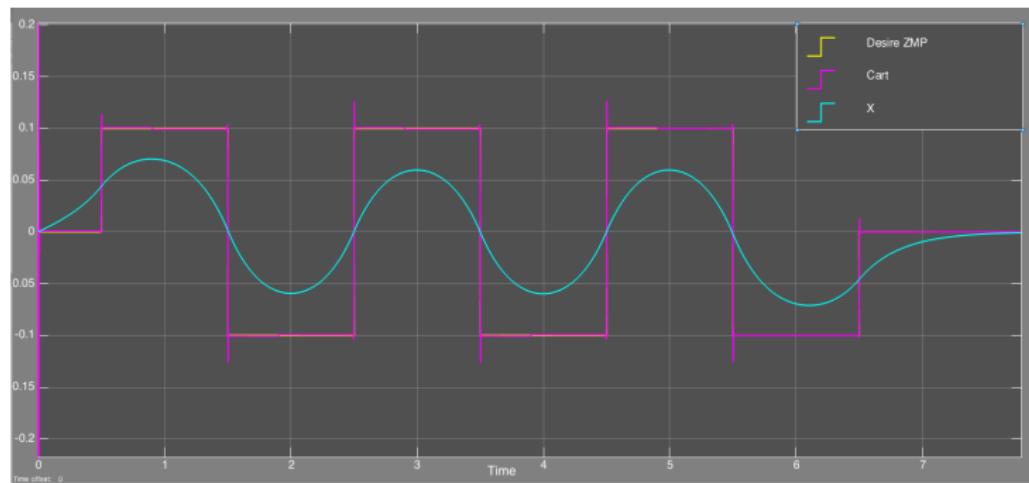
- Preview controller is defined by its coefficients, and number of preview steps
- These coefficients can be found by cost function optimization introduced in (Katayama et al. (1985))



Preview controlled cart table

# Implementation and Evaluation: Preview controller

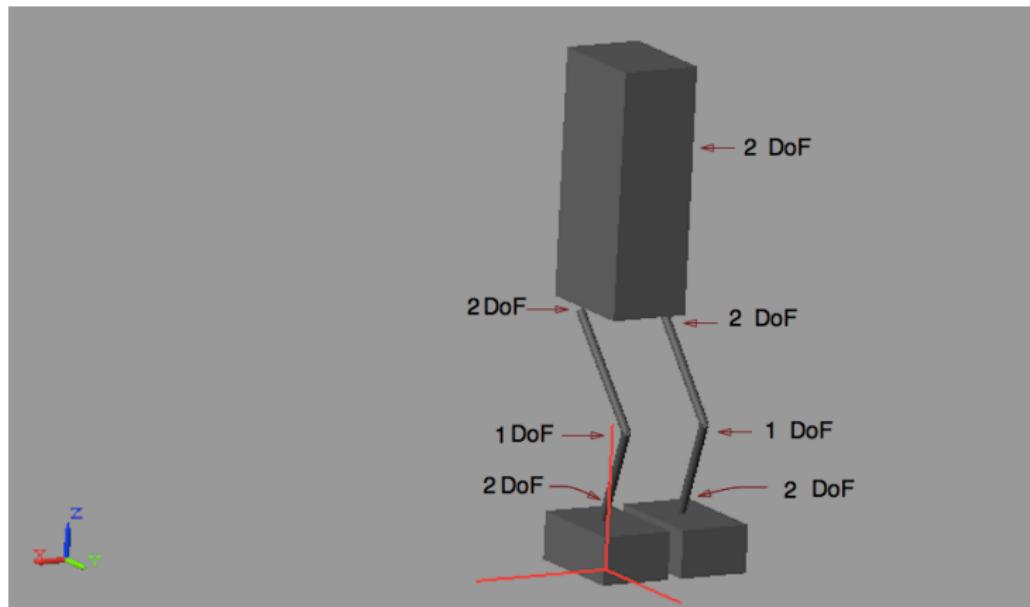
The results of preview control show that it can be applied for such unstable system as cart on table is



Preview controlled cart table model results

# Implementation and Evaluation: Preview controller for robot model

We use 12 DoF robot model in simulink environment



12 DoF robot model

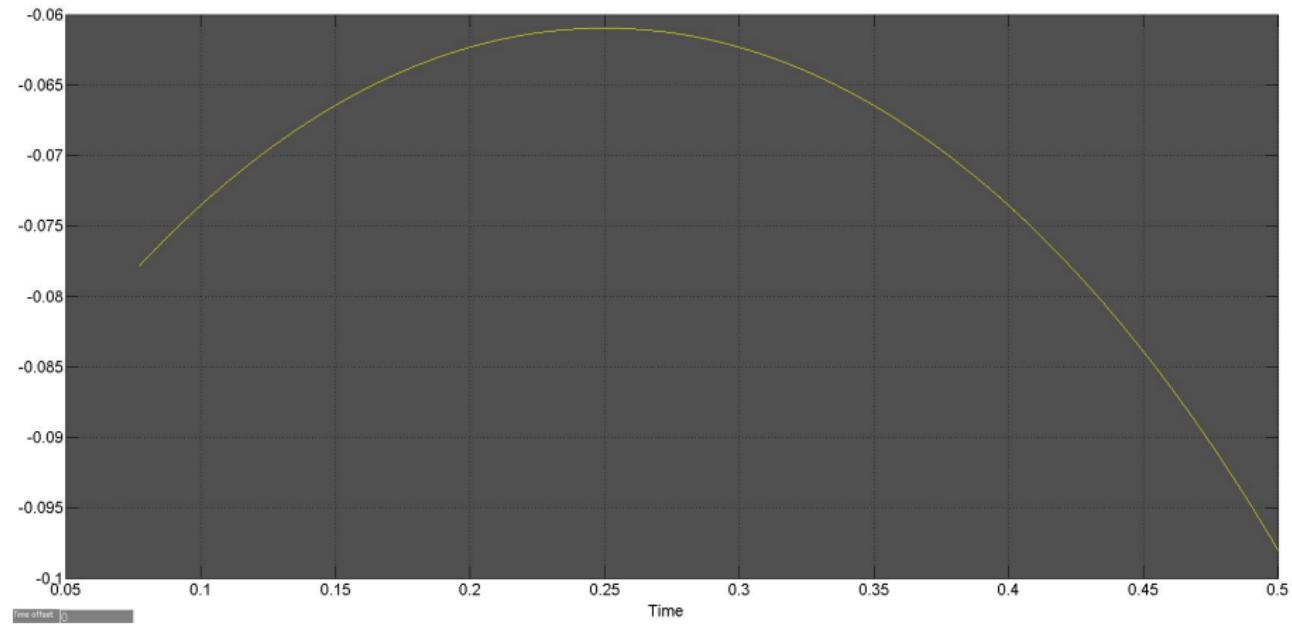
# Implementation and Evaluation

## Trajectories

- During each step we want ZMP to be located in one point under the foot
- Trajectory of robot CoM is the solution of the following equation:

$$x - \frac{Z_c}{g} \ddot{x} = 0 \quad (13)$$

# Implementation and Evaluation: Trajectories

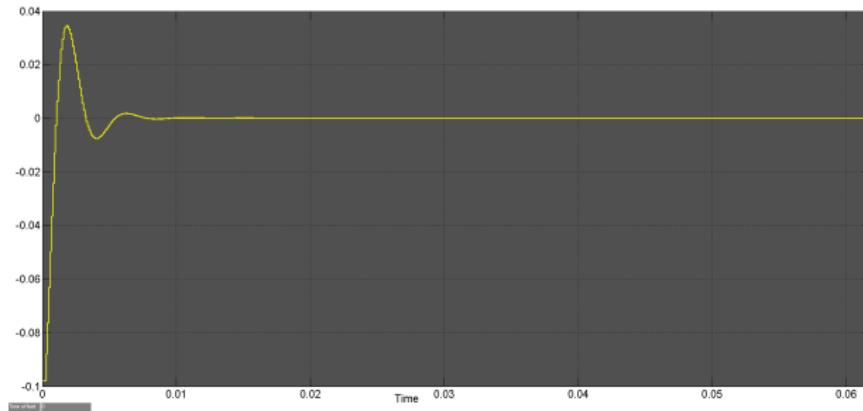


Analytically generated CoM trajectory

# Implementation and Evaluation

## Trajectories

- Preview control was applied to the model of robot
- The results are perfect but physically unreachable



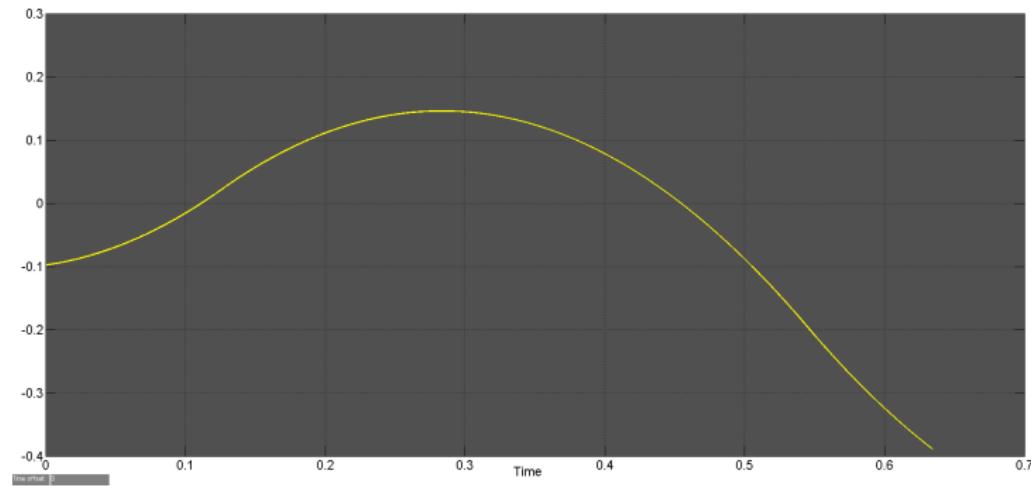
Ideal preview control results

# Implementation and Evaluation

## Trajectories

- Preview control was applied to the model of robot with limitation of maximum acceleration
- The results become close to analytical one

# Implementation and Evaluation



Limited preview control results

# Implementation and Evaluation

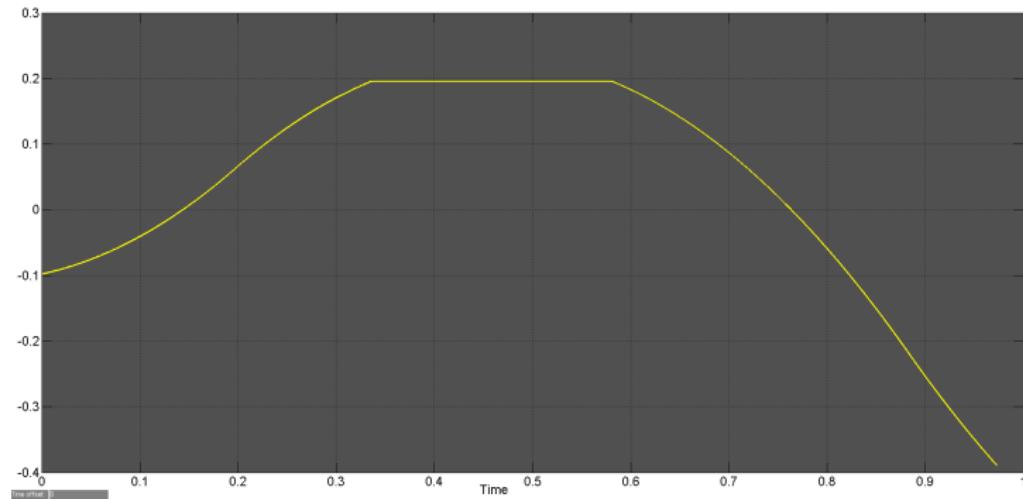
## Trajectories

- (Choi and Lee (2006)) considers modified form of control signal
- 

$$u(k) = -G_I e(i) - G_x x(k) - \sum_{l=1}^{N_I} G_d(l) y_d(k+l) \quad (14)$$

# Implementation and Evaluation

The result of modified preview controller with the same parameters



Limited preview control results

## Future Work

- Develop a model that is more similar to a real robot
- Develop an inverse kinematics module that takes CoM trajectory and generates trajectories for all other joints
- Combine two controllers in sagittal and frontal planes
- Apply preview controller to a real robot

# Summary

- Different approaches to bipedal locomotion
- It was implemented solution consisted of Central Pattern Generator approach (preview controller) and Zero Moment Point criterion
- Alternative structure of preview controller
- Evaluation of results shows that Preview control is a perspective approach for bipedal locomotion
- Physical motors restrictions can be applied to the model

# Thanks for the attention

Now it's time for your questions



Wall-e (Stanton (2015))

# Materials

$$\begin{aligned} X_{CoG}(t) &= X_{CoG}(0)\cosh\left(\sqrt{\frac{g}{\alpha Z_{CoG}}}t\right) + \sqrt{\frac{\alpha Z_{CoG}}{g}}\dot{X}_{CoG}(0)\sinh\left(\sqrt{\frac{g}{\alpha Z_{CoG}}}t\right) \\ Y_{CoG}(t) &= Y_{CoG}(0)\cosh\left(\sqrt{\frac{g}{\beta Z_{CoG}}}t\right) + \sqrt{\frac{\beta Z_{CoG}}{g}}\dot{Y}_{CoG}(0)\sinh\left(\sqrt{\frac{g}{\beta Z_{CoG}}}t\right) \end{aligned} \quad (15)$$

## Materials

$$\tau_1 \dot{x}_1 = -x_1 - \beta f(\nu_1) - \gamma f(x_2) + u_0 + u_{f_1} \quad (16)$$

$$\tau_2 \dot{\nu}_1 = -\nu_1 + f(x_1) \quad (17)$$

$$\tau_1 \dot{x}_2 = -x_2 - \beta f(\nu_2) - \gamma f(x_1) + u_0 + u_{f_2} \quad (18)$$

$$\tau_2 \dot{\nu}_2 = -\nu_2 + f(x_2) \quad (19)$$

where  $x_1$  is initial state of neuron, fired by the constant input  $u_0$ ,  $x_1$ ,  $x_2$ ,  $\nu_1$  and  $\nu_2$  are state variables, dot represents time derivative. When firing reaches some threshold, the neuron goes to state  $\nu_1$  through eq. (17). When it exceeds some threshold it starts to return to the state  $x_1$  through the eq. (16) by the factor  $\beta$ .  $\beta$  represents the rate of adaptations, if  $\beta$  is big, the return to state  $x_1$  is fast.  $u_{f_1}$  and  $u_{f_2}$  are the feedback inputs from sensors,  $\gamma$  is the coefficient between state variables and  $f(x)$  is a threshold function that has zero gain until  $x$  is less than threshold value and not zero gain otherwise . Such element works the following way: when it takes constant input it reacts, then adapts and stop reacting. Oscillations generation is the process of reaction and adaptation itself.

## Materials

Matsuoka in Matsuoka (1985) discusses oscillations generated by mutual inhibition between  $n$  neurons with adaptation:

$$\begin{aligned}\dot{x}_i + x_i &= - \sum_{j=1}^n a_{ij}y_j - bx' + s_i \\ T\dot{x}'_i + x'_i &= y_i \\ y &= g(x_i) \quad (i = 1, \dots, n)\end{aligned}\tag{20}$$

where  $a_{ij}$  represents the strength of inhibitory connection between the neurons.  $a_{ij} > 0$  for  $i \neq j$  and  $a_{ii} = 0$  for  $i = j$ .  $\sum_{j=1}^n a_{ij}y_j$  is the total input from the neurons inside a neural network and  $s_i$  is the total input from the outside of the network,  $y_j$  is input from neuron  $j$ .

## Materials

$$u(k) = -G_I \sum_{i=0}^k e(i) - G_x x(k) - \sum_{l=1}^N G_d(l) y_d(k+l) \quad (21)$$

Where  $G_I = [R + \tilde{B}^T \tilde{K} \tilde{B}]^{-1} \tilde{B}^T \tilde{K} \tilde{I}$  represents integral coefficient,  $e(i)$  is an error between controlled value and its referenced value,

$G_x = [R + \tilde{B}^T \tilde{K} \tilde{B}]^{-1} \tilde{B}^T \tilde{K} \tilde{F}$  represents proportional coefficient,  $x(k)$  is the controlled value,  $G_d(1) = -G_I$  and  $G_d(l) = [R + \tilde{B}^T \tilde{K} \tilde{B}]^{-1} \tilde{B}^T \tilde{X}(l-1)$  represents feature coefficients at time  $l$ ,  $y_d(t)$  is a value of reference signal at time  $t$ .

with the solution of DARE  $\tilde{K}$  in the form:

$$\tilde{K} = \tilde{A}^T \tilde{K} \tilde{A} - \tilde{A}^T \tilde{K} \tilde{B} [R + \tilde{B}^T \tilde{K} \tilde{B}]^{-1} \tilde{B}^T \tilde{K} \tilde{A} + \tilde{Q} \quad (22)$$

where:

$$\tilde{B} = \begin{bmatrix} CB \\ B \end{bmatrix}, \tilde{I} = \begin{bmatrix} I_p \\ 0 \end{bmatrix}, \tilde{F} = \begin{bmatrix} CA \\ A \end{bmatrix}, \tilde{Q} = \begin{bmatrix} Q_e & 0 \\ 0 & Q_x \end{bmatrix}, \tilde{A} = [\tilde{I} \quad \tilde{F}] \quad (23)$$

## Materials

$$X_{CoM} = C_1 e^{-\omega t} + C_2 e^{\omega t} \quad (24)$$

where  $C_1 = \frac{0.2(1 + e^{0.5\omega})}{(e^{-0.5\omega} - e^{0.5\omega})}$ ,  $C_2 = -0.2 - C_1$ ,  $\omega = \sqrt{\frac{g}{Z_c}}$ , g is the gravitational acceleration,  $Z_c$  is robot's CoM height.

# Materials

$$J = \sum_{i=k}^{\infty} \{ e^T(i) Q_e e(i) + \Delta x^T(i) Q_x \Delta x(i) + \Delta u^T(i) R \Delta u(i) \} \quad (25)$$