Development and implementation dynamic balance algorithms for bipedal robot locomotion

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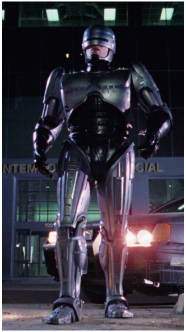
Introduction and Motivation: the development of robotics in minds

Universal robots applications

Forbidden planet, 1956



Robocop, 1987

Bicentennial man, 1999

Introduction and Motivation

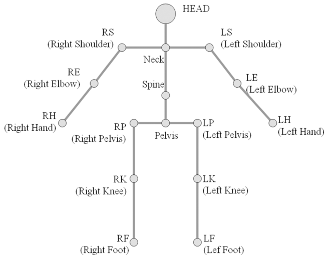
Humanoids Advantages and Disadvantages

- (+) Environment that is the same as humans'
- (+) Natural, human-like
- (+) Uneven terrains
- (-) Difficult locomotion control
- (-) Complex design
- (-) Low speed
- (?) 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

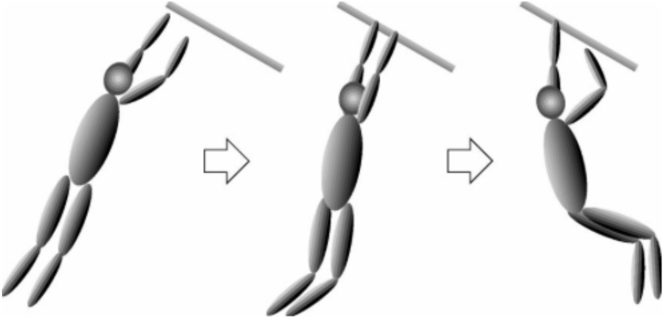


Human represented as a set of kinematic chains, (Seo et al. (2011))

Problem Overview

Bipedal locomotion difficulties

- Motions planning



Human structure changing (Nakamura and Yamane (2000))

Related work

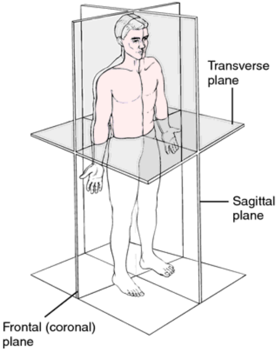
Bipedal locomotion control approaches

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

Theoretical Aspects of Bipedal Robots Control

Human planes intersting for locomotion

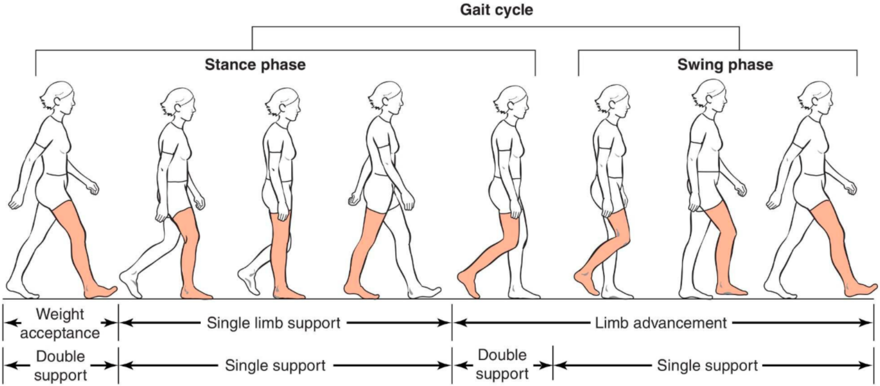
- Sagittal plane
- Frontal plane



Human planes (Stedman (2015))

Theoretical Aspects of Bipedal Robots Control

Locomotion is a periodic gait cycle.

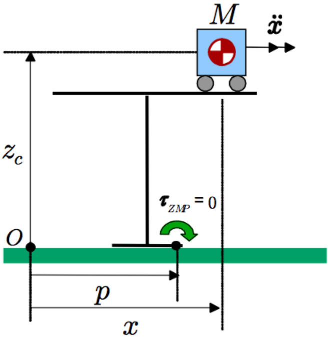


Gait cycle decomposition (Hill (2015))

Theoretical Aspects of Bipedal Robots Control

Cart table model

- (+) Represents ZMP
- (-) Doesn't consider additional DoF

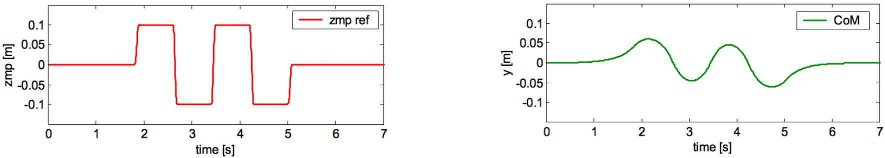


Cart table model (Kajita et al. (2003))

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 a robot in order to follow the pattern



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

Theoretical Aspects of Bipedal Robots Control: Preview Control

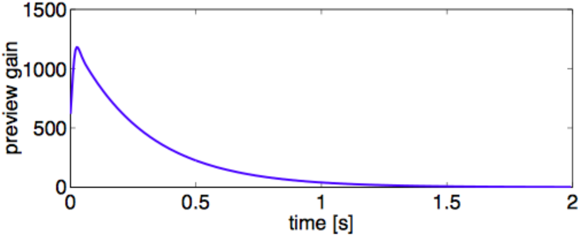
Preview Control

- 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:

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

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?

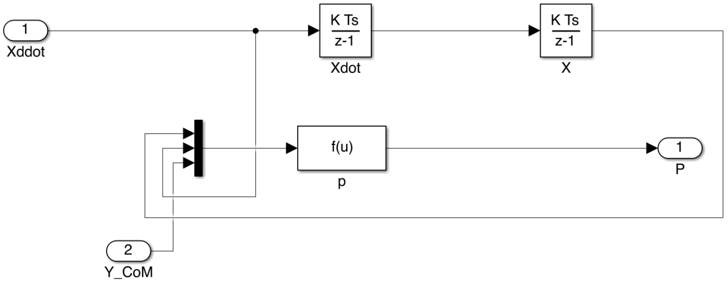
- Implementation of cart table model
- Implementation of PID controlled cart table model
- Implementation of preview controlled cart table model
- Comparison of preview and PID control result
- Preview control was applied to a robot model

Implementation and Evaluation: Cart table model

Cart table model

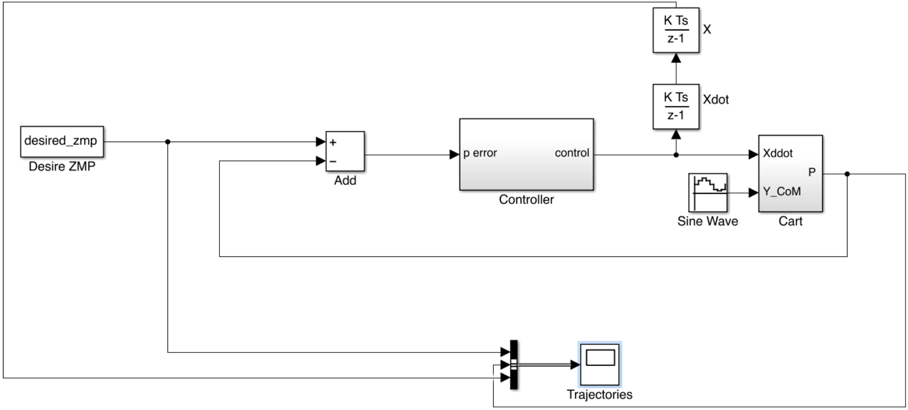
- Can be described by the following equation:

$$P = x - \frac{Z_c}{g}\ddot{x} \tag{2}$$



Cart table model in simulink environment

Implementation and Evaluation: PID controlled cart table model

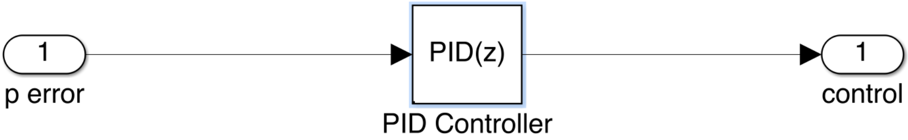


PID controlled cart table

Implementation and Evaluation: PID controller

PID controller

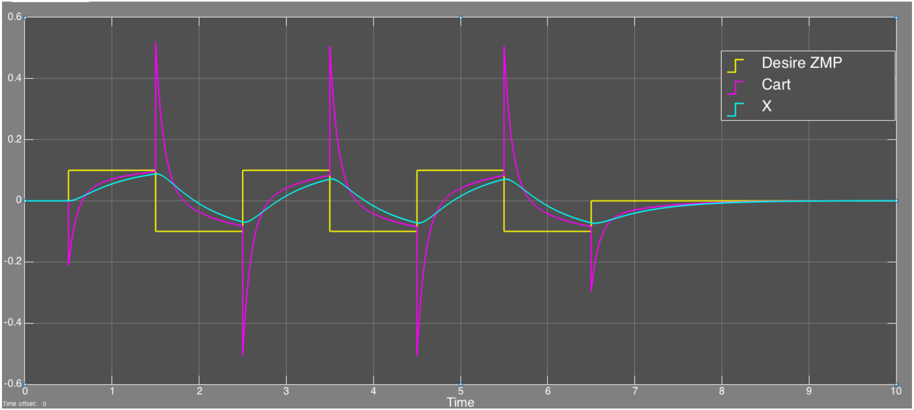
- PID controller is defined by its coefficients
- Coefficients can be adjusted by several algorithms: response analysis, transfer function analysis
- In this work matlab proprietary algorithm was used



PID controller

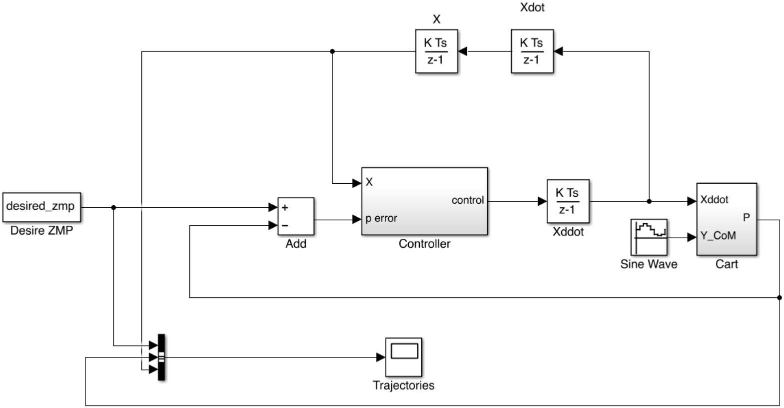
Implementation and Evaluation: PID controller

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

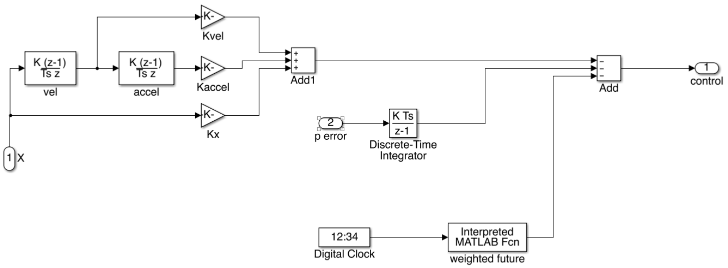


Preview controlled cart table

Implementation and Evaluation: Preview controller

Preview controller

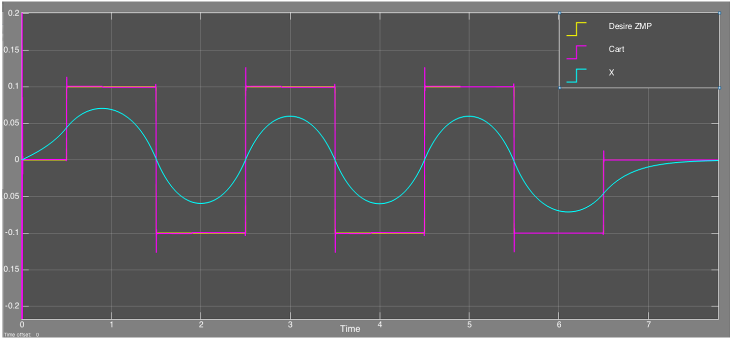
- Preview controller is defined by its coefficients, and number of preview steps
- These coefficients can be found by cost function optimization introduced in (Katayama et al. (1985))



Preview controlled cart table

Implementation and Evaluation: Preview controller

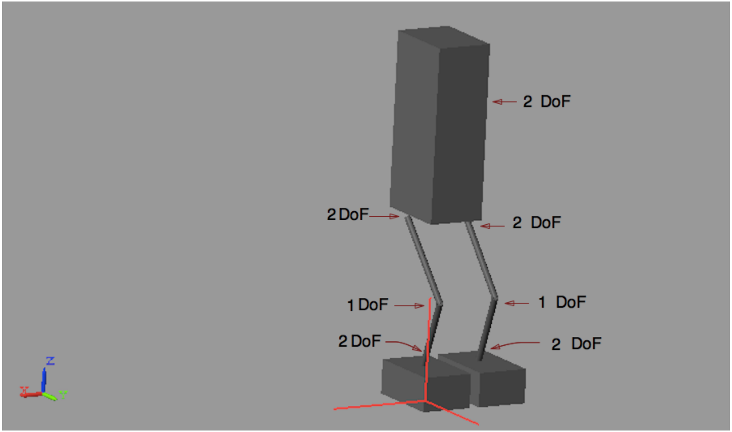
The results of preview control show that it can be applied for such unstable system as cart on table is



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

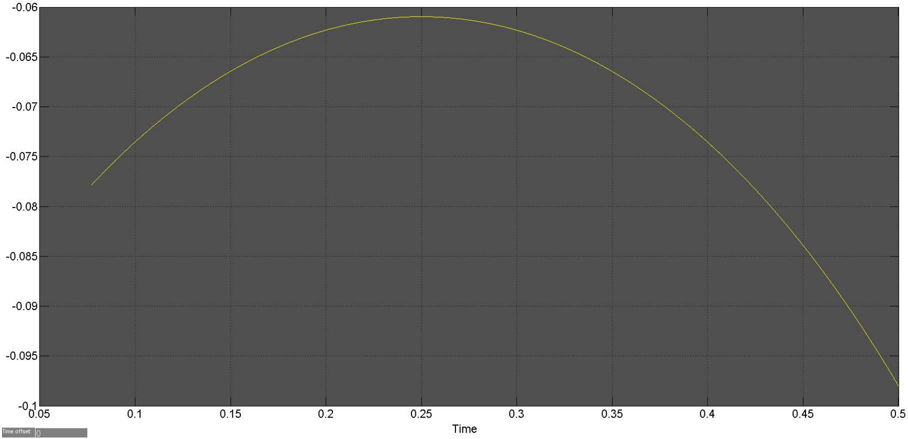
Implementation and Evaluation

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:

$$x - \frac{Z_c}{g}\ddot{x} = 0 \tag{3}$$

Implementation and Evaluation: Trajectories

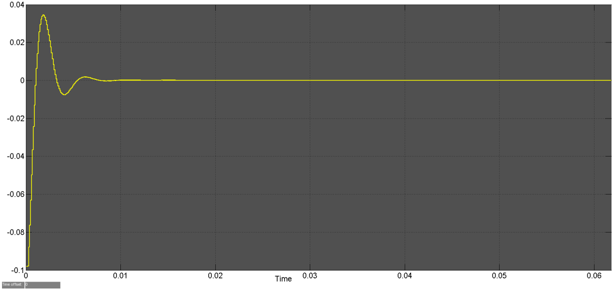


Analytically generated CoM trajectory

Implementation and Evaluation

Trajectories

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



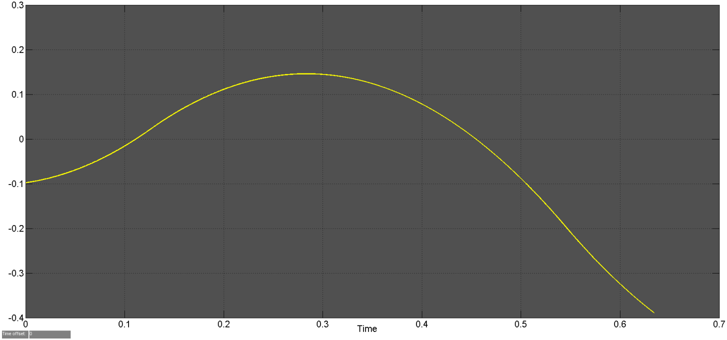
Ideal preview control results

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

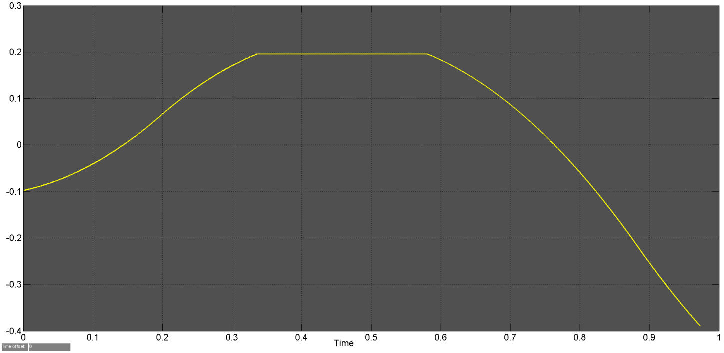
Implementation and Evaluation

Trajectories

- (Choi and Lee (2006)) considers modified form of control signal
-
$$u(k) = -G_I e(i) - G_x x(k) - \sum_{l=1}^{N_l} G_d(l) y_d(k+l) \tag{4}$$

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 were considered
- The solution comprising Central Pattern Generator approach + Adaptive control (preview controller) + Analytical approach (Zero Moment Point criterion) was implemented
- Alternative structure of the preview controller was considered and evaluated
- Evaluation of the results shows that the Preview controller is a perspective approach for bipedal locomotion control
- Physical motors restrictions can were applied to the model, resulting in a more accurate model

Thanks for the attention

Now it's time for your questions

Wall-e (Stanton (2015))

Materials

$$X_{CoG}(t) = X_{CoG}(0)cosh\left(\sqrt{\frac{g}{\alpha Z_{CoG}}}t\right) + \sqrt{\frac{\alpha Z_{CoG}}{g}}\dot{X}_{CoG}(0)sinh\left(\sqrt{\frac{g}{\alpha Z_{CoG}}}t\right)$$

$$Y_{CoG}(t) = Y_{CoG}(0)cosh\left(\sqrt{\frac{g}{\beta Z_{CoG}}}t\right) + \sqrt{\frac{\beta Z_{CoG}}{g}}\dot{Y}_{CoG}(0)sinh\left(\sqrt{\frac{g}{\beta Z_{CoG}}}t\right) \quad (5)$$

Materials

$$\tau_1 \dot{x}_1 = -x_1 - \beta f(\nu_1) - \gamma f(x_2) + u_0 + u_{f_1} \tag{6}$$

$$\tau_2 \dot{\nu}_1 = -\nu_1 + f(x_1) \tag{7}$$

$$\tau_1 \dot{x}_2 = -x_2 - \beta f(\nu_2) - \gamma f(x_1) + u_0 + u_{f_2} \tag{8}$$

$$\tau_2 \dot{\nu}_2 = -\nu_2 + f(x_2) \tag{9}$$

where x_1 is initial state of neuron, fired by the constant input u_0, x_1, x_2, ν_1 and ν_2 are state variables, dot represents time derivative. When firing reaches some threshold, the neuron goes to state ν_1 through eq. (7). When it exceeds some threshold it starts to return to the state x_1 through the eq. (6) by the factor β. β represents the rate of adaptations, if β is big, the return to state x_1 is fast. u_{f_1} and u_{f_2} are the feedback inputs from sensors, γ 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:

$$\begin{aligned} \dot{x}_i + x_i &= -\sum_{j=1}^{n} a_{ij} y_j - b x' + s_i \\ T\dot{x}_i' + x_i' &= y_i \\ y = g(x_i) & \quad (i = 1, ..., n) \end{aligned} \tag{10}$$

where a_{ij} represents the strength of inhibitory connection between the neurons. $a_{ij} > 0$ for i≠j and $a_{ij} = 0$ 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

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

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:

$$\tilde{K} = \tilde{A}^T \tilde{K} \tilde{A} - \tilde{A}^T \tilde{K} \tilde{B} [R + \tilde{B}^T \tilde{K} \tilde{B}]^{-1} \tilde{B}^T \tilde{K} \tilde{A} + \tilde{Q} \qquad (12)$$

where:

$$\tilde{B} = \begin{bmatrix} CB \\ B \end{bmatrix}, \tilde{I} = \begin{bmatrix} I_p \\ 0 \end{bmatrix}, \tilde{F} = \begin{bmatrix} CA \\ A \end{bmatrix}, \tilde{Q} = \begin{bmatrix} Q_e & 0 \\ 0 & Q_x \end{bmatrix}, \tilde{A} = \begin{bmatrix} \tilde{I} & \tilde{F} \end{bmatrix} \qquad (13)$$

Materials

$$X_{CoM} = C_1 e^{-\omega t} + C_2 e^{\omega t} \tag{14}$$

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

Materials

$$J = \sum_{i=k}^{\infty} \{ e^T(i) Q_e e(i) + \triangle x^T(i) Q_x \triangle x(i) + \triangle u^T(i) R \triangle u(i) \} \tag{15}$$

Related work: Analytical approach

Steps required for bipedal locomotion

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

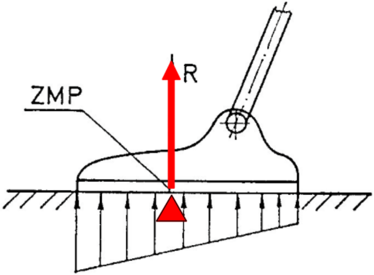
Stability measures

- 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

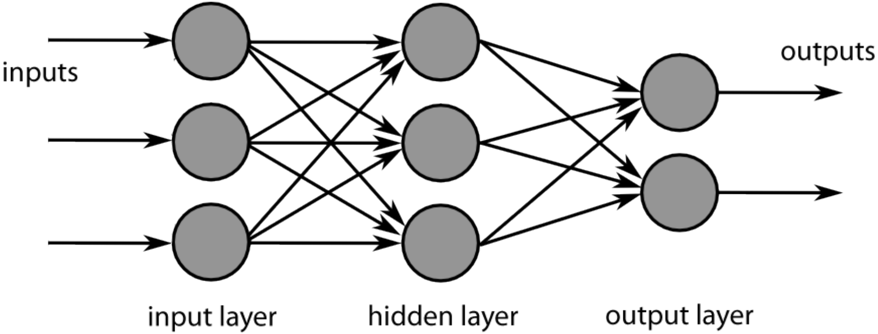
- Rhythm generating
- Control and adaptation mechanism

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

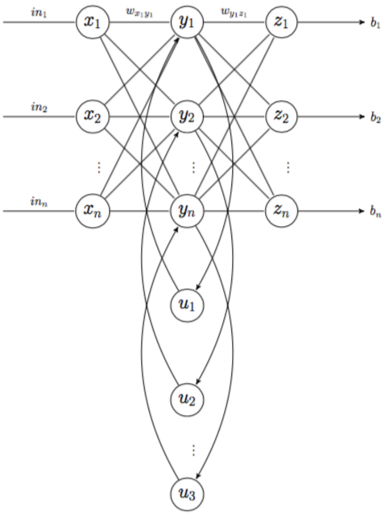
Feed-Forward Networks



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

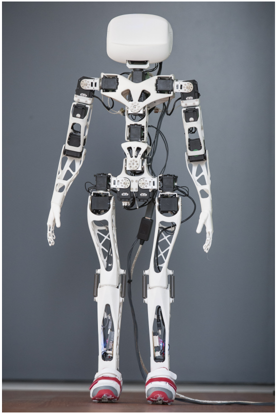
Introduction and Motivation: humanoid robots development

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

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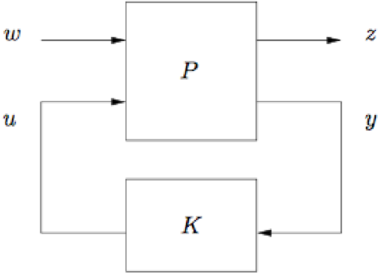
Optimal Control

- 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

$$x(k+1) = Ax(k) + Bu(k)$$
$$y(k) = Cx(k) + Du(k) \tag{16}$$

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

- Transfer function

$$G(Z) = C(ZI - A)^{-1}B + D \tag{17}$$

Where Z is Z transform variable

Theoretical Aspects of Bipedal Robots Control: Optimal Control

Optimal Control

- Transfer function measures

$$||G(Z)||_2 = Trace\{B^T XB + D^T D\} \tag{18}$$

- X should satisfy:

$$X = A^T XA + C^T C \tag{19}$$

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

Theoretical Aspects of Bipedal Robots Control: Optimal Control

Optimal Control

- Transfer function measures

$$||G(Z)||_\infty = \sup_{\omega} \frac{||z||_2}{||\omega||_2} \tag{20}$$

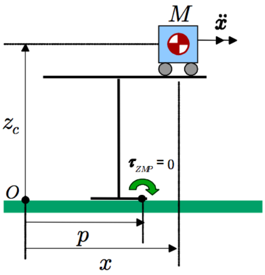
- $$z = G\omega \tag{21}$$

- ω 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: cart table model

Cart table model

- M is cart mass
- x is cart trajectory
- $\ddot{x}$ is cart acceleration
- p is ZMP coordinate



Theoretical Aspects of Bipedal Robots Control: cart table model

Cart table model

- Z_c is height of cart CoM
- τ_{ZMP} is rotational moment in ZMP
- Cart table dynamics:

$$P = x - \frac{Z_c}{g}\ddot{x} \tag{22}$$