DynamicWalking2008, Delft, Netherlands,
Thursday, May 29, 2008

Overview of ZMP-based Biped Walking

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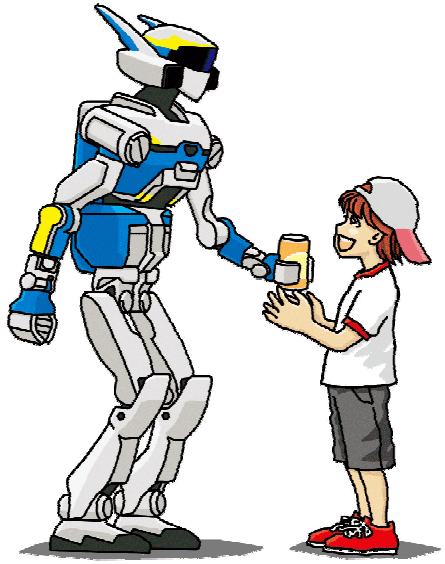
AIST, Japan

ZMP-based Biped Walking

- **What we can do with ZMP?**
- What is ZMP?
  - Definition
  - Trajectory generation
  - Stabilization control
- Our current project



Humanoid robot HRP-2

1.54m, 58kg, 30DoF

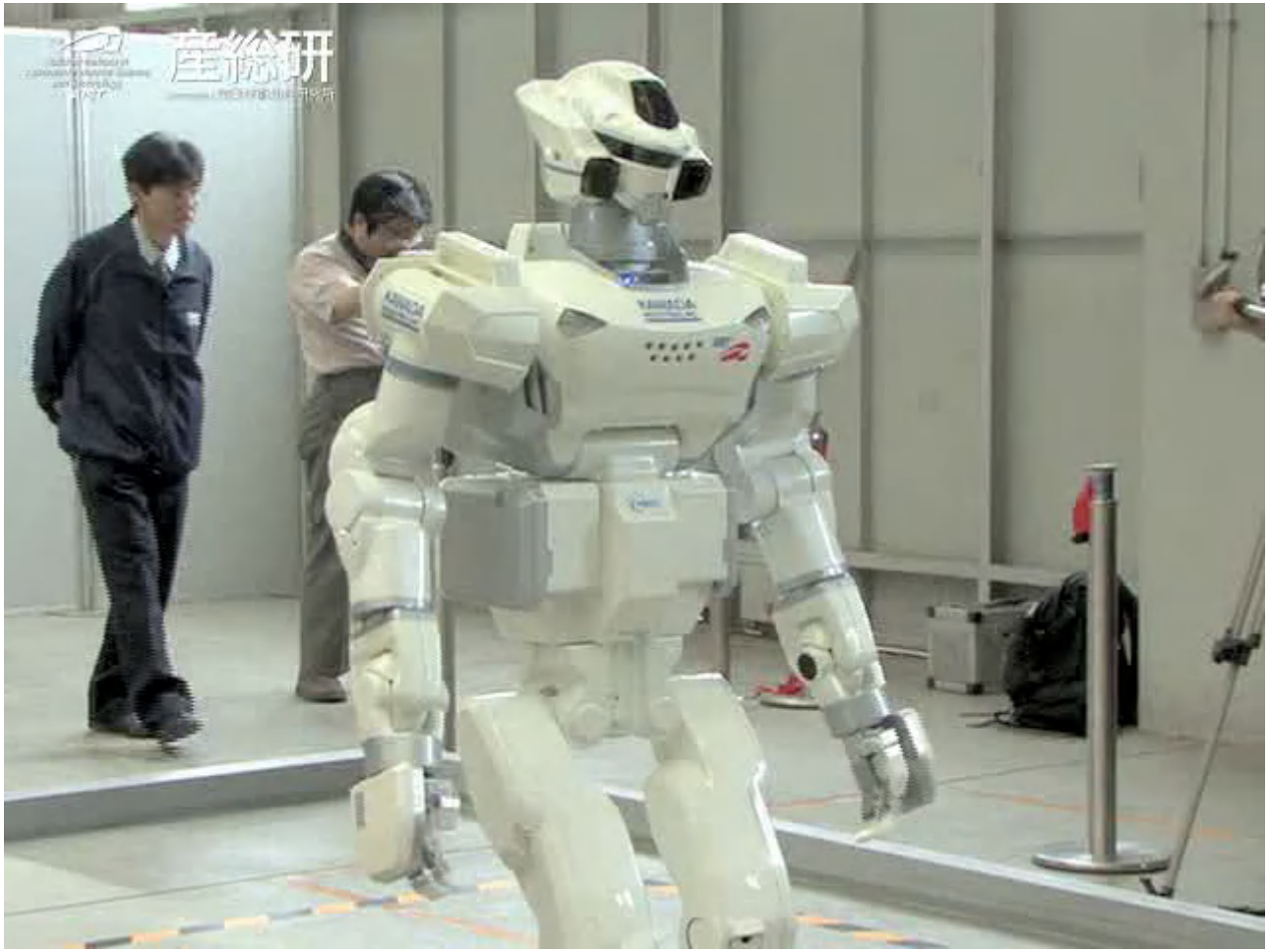
Now used at

- AIST
- Four universities in Japan
- LAAS Toulouse, France

Kawada Industries Co. and AIST, 2002

Real-time gait generation

HRP-3



1.6m, 68kg, 42DoF and water resistant

Kawada industries Co . and AIST, 2007

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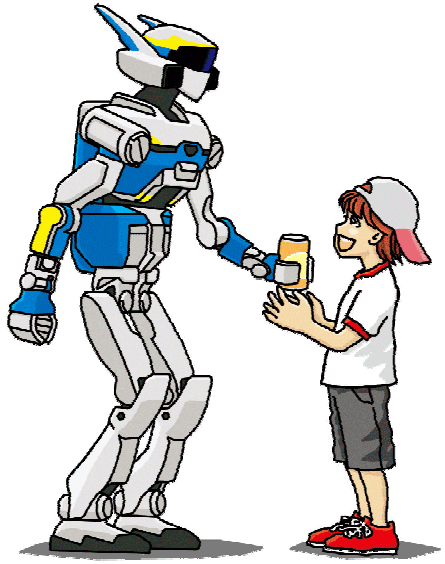


What is ZMP?

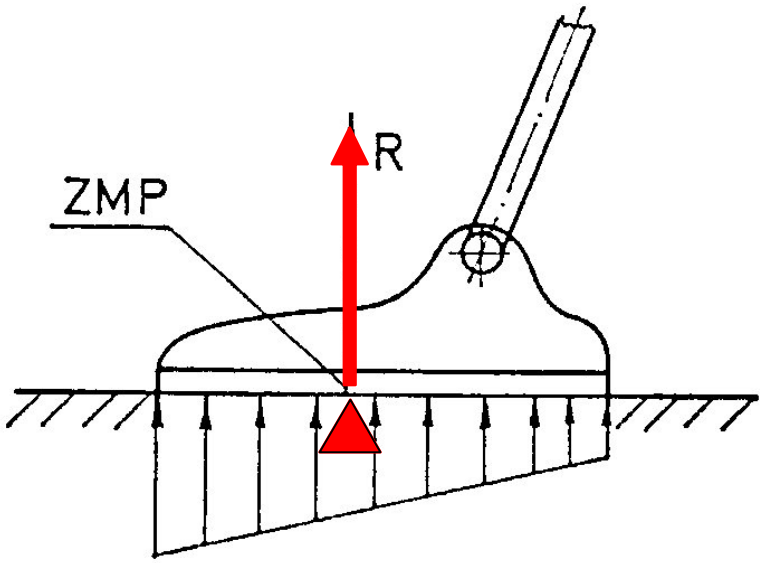


FIG. 1. Zero-moment point (ZMP).

Vukobratovic and Stepanenco,1972

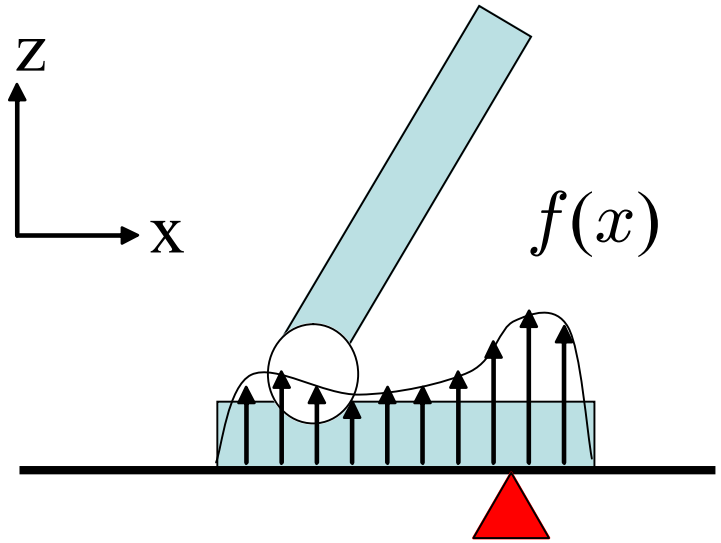
Miomir Vukobratovic

The distributed floor reaction force can be replaced by a single force R acts on Zero-moment Point (ZMP).

ZMP = Center of Pressure (CoP)

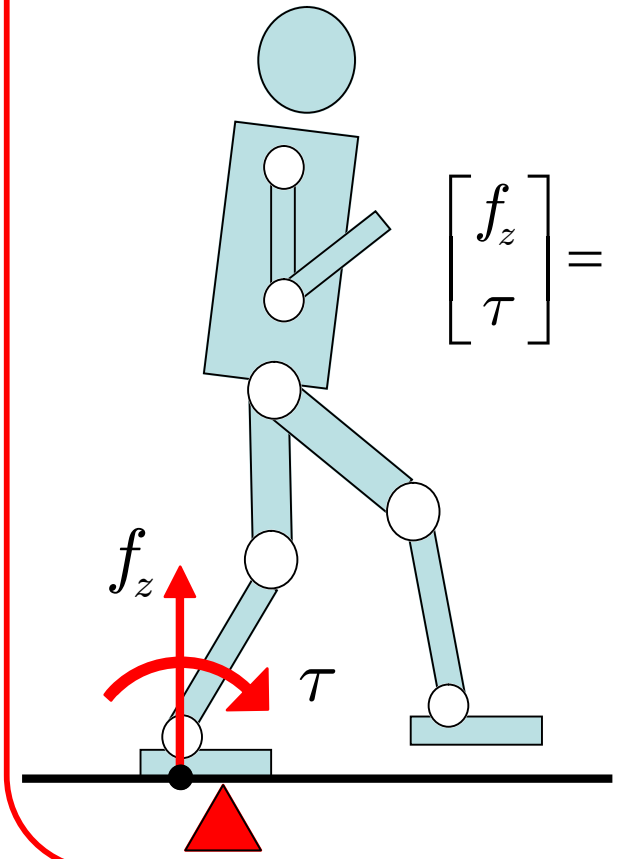
Two ways to get ZMP

Ground Reaction Force (GRF) measurement



ZMP $p = \dfrac{\int x f(x) dx}{\int f(x) dx}$

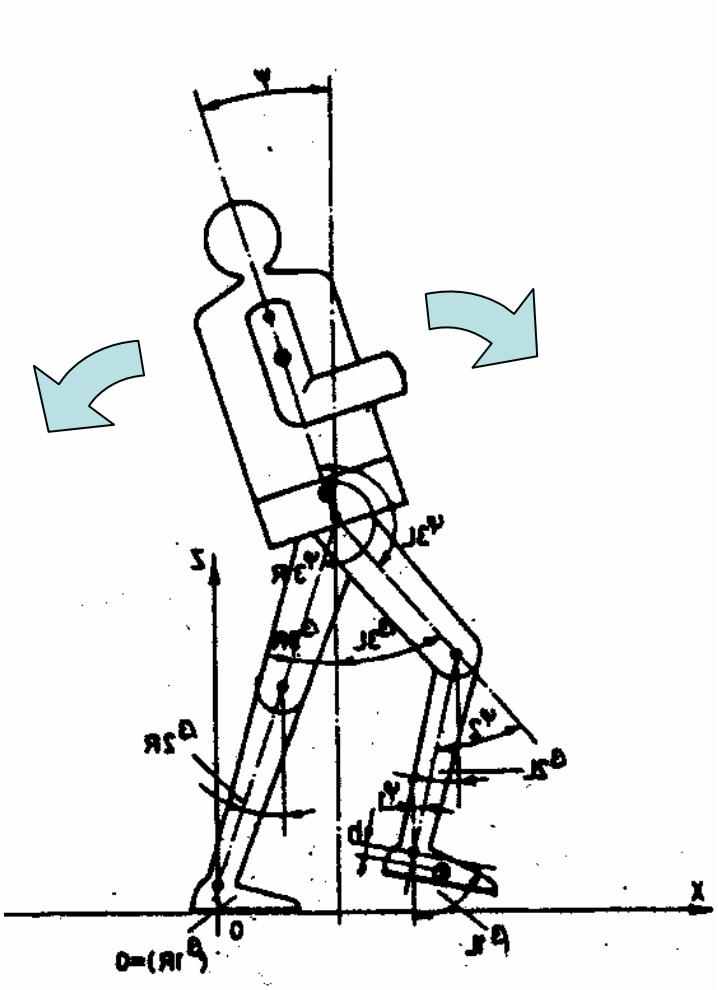
Inverse Dynamics



$$\begin{bmatrix} f_z \\ \tau \end{bmatrix} = InvDyn(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}})$$

ZMP $p = -\dfrac{\tau}{f_z}$

Vukobratovic's idea

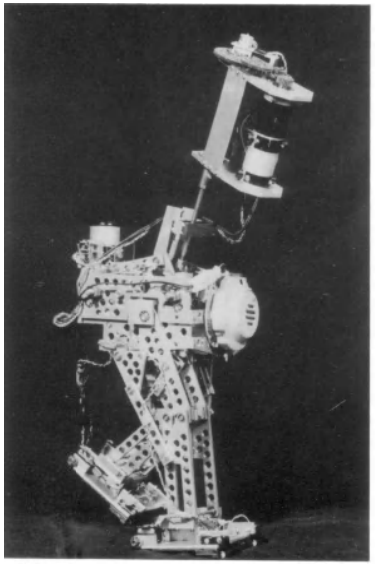


1. Leg motion is prepared in advance
2. Upper body motion is calculated so that the ZMP(CoP) exists in the expected supporting foot

A robot with compensating mass

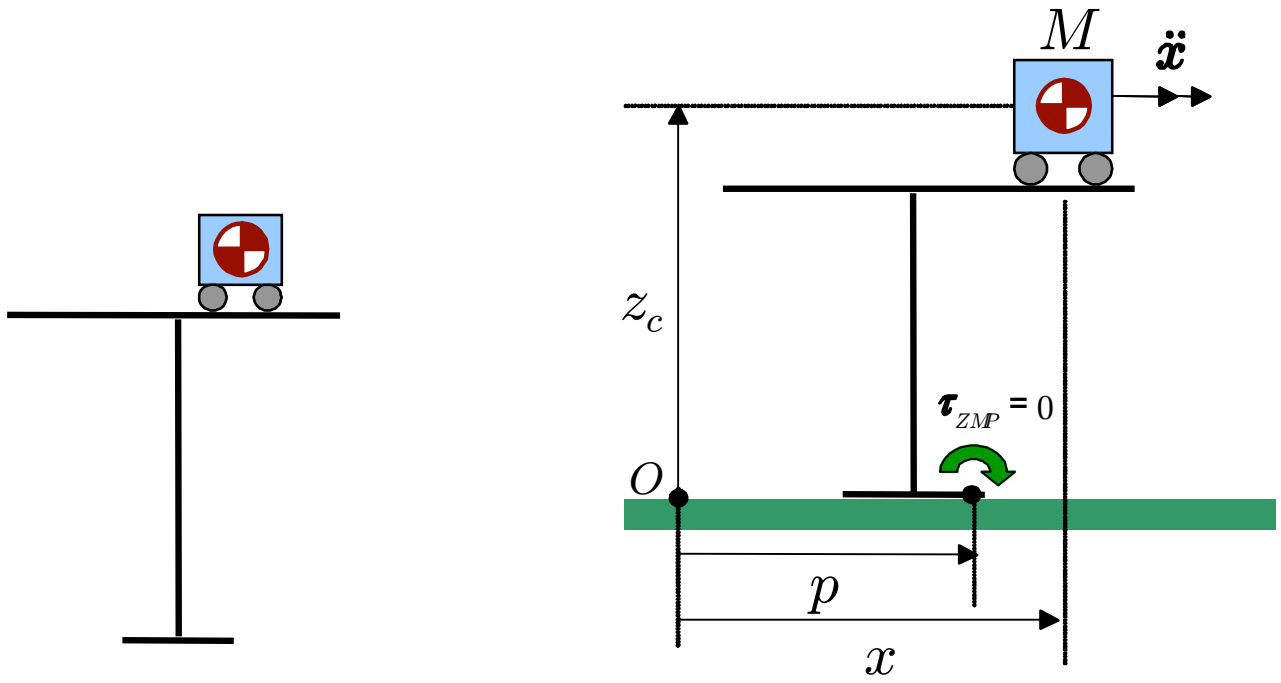
Funabashi et al. 1982

Advance in two decades



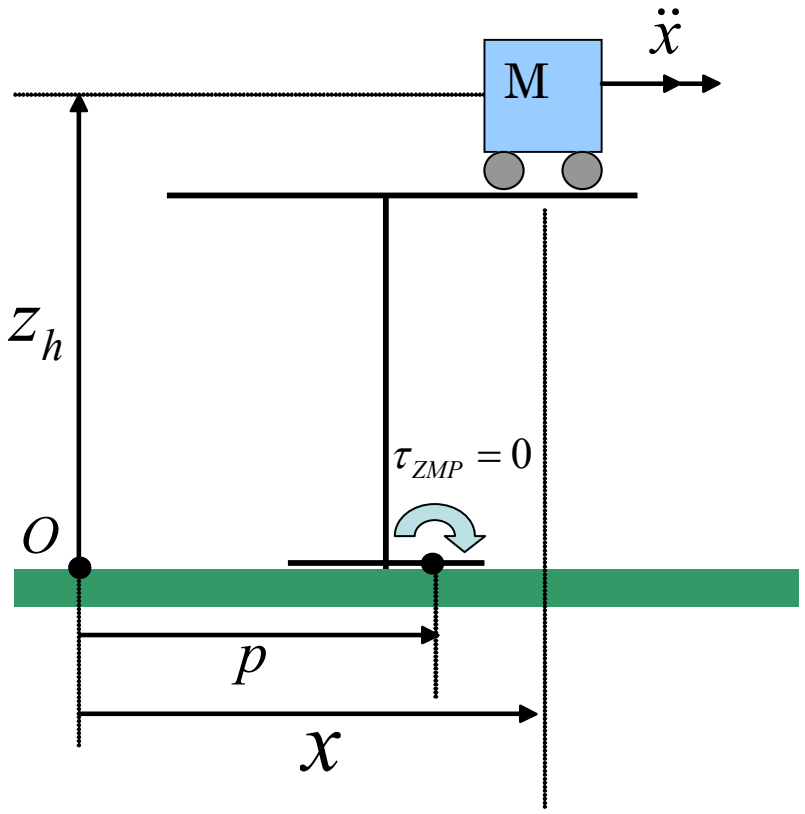
	MEG-2 (1982)	HRP-2 (2002)
Actuators	70 [W/kg]	600 [W/kg]
Upper body mass	Small	Large
Computer	4.0MHz	1.6GHz

Simplified model for dynamics



- a running cart on a mass-less table
- the cart represents the center of mass motion
- the table represents the supporting foot

ZMP of the Cart-Table Model



Balance of moment

$$\tau_{ZMP} = Mg(x - p) - M\ddot{x}z_h$$
$$= 0$$

ZMP equation

$$p = x - \frac{z_h}{g}\ddot{x}$$

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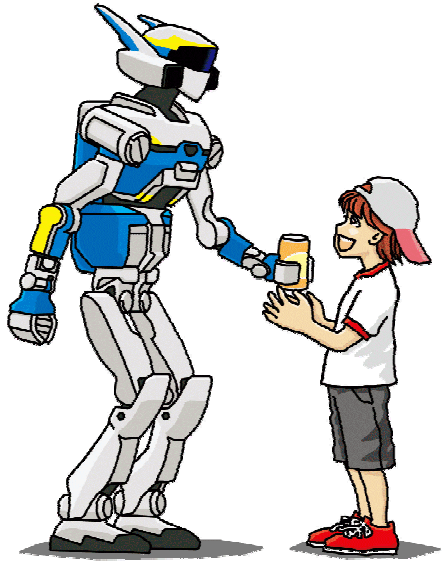
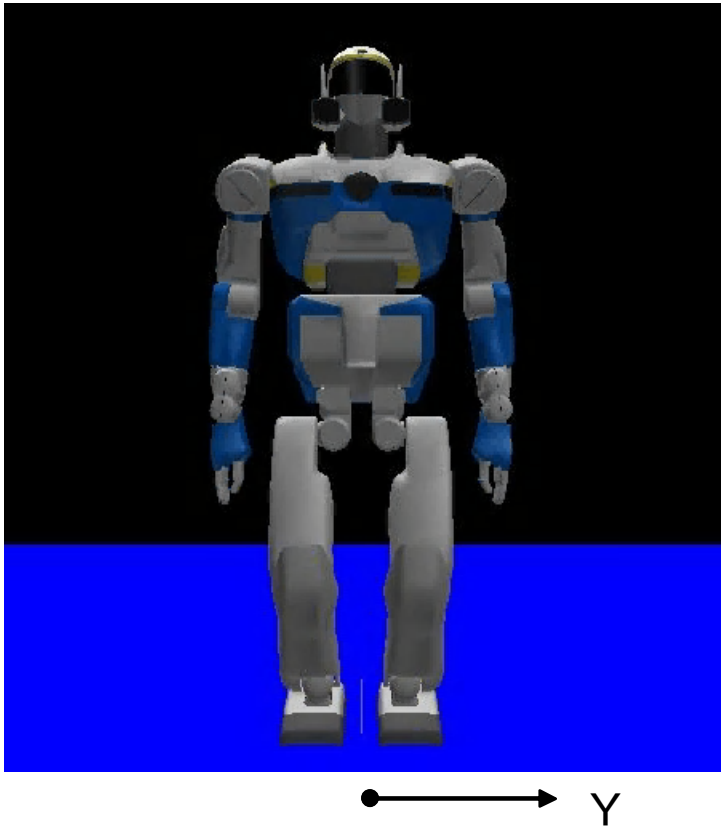
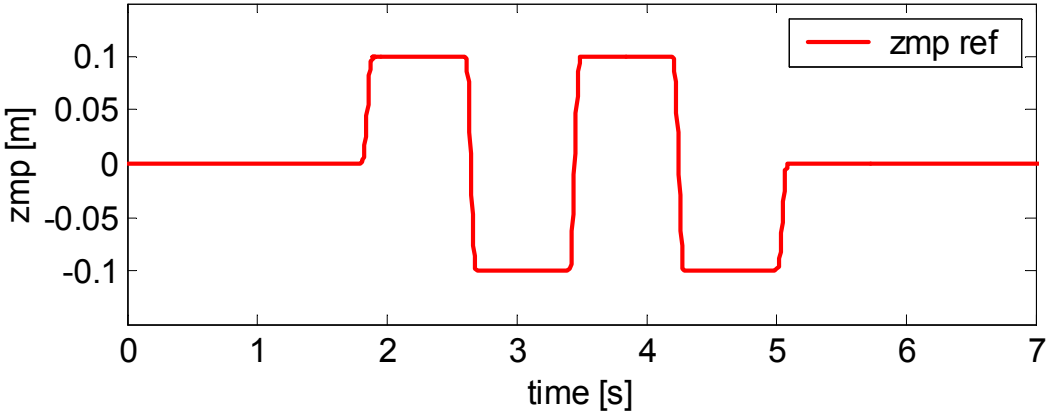


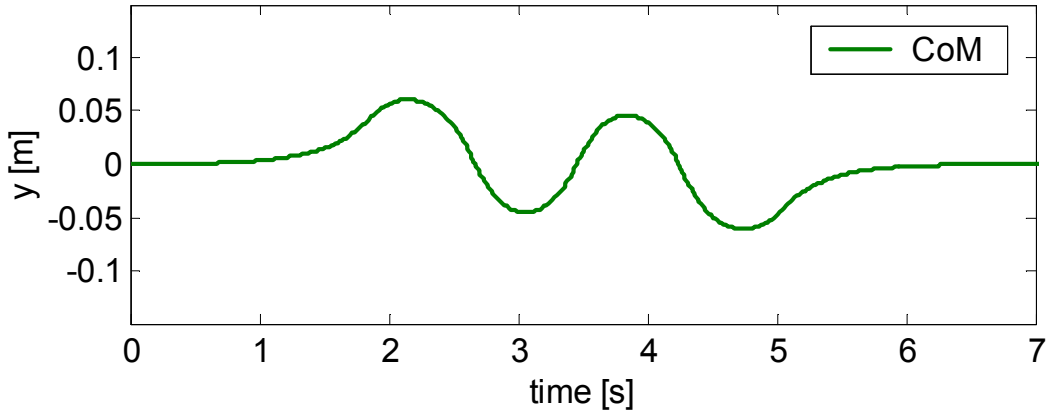
ZMP based pattern generation



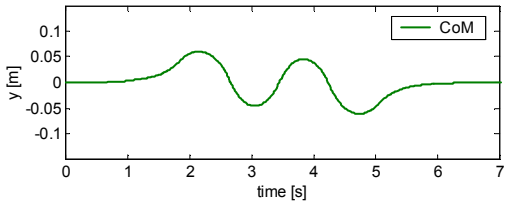
Target ZMP pattern



Trajectory of center of mass

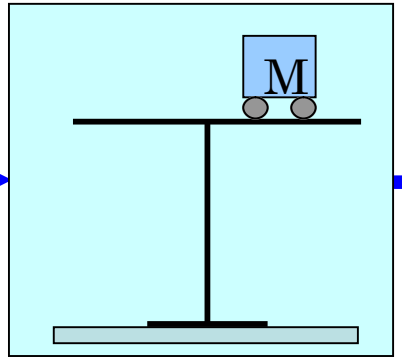


Input and Output

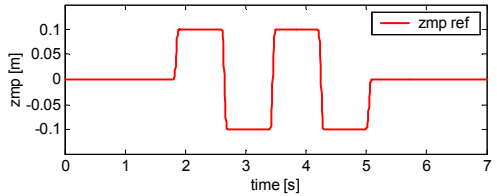


x

Cart trajectory



$$p = x - \frac{z_h}{g}\ddot{x}$$

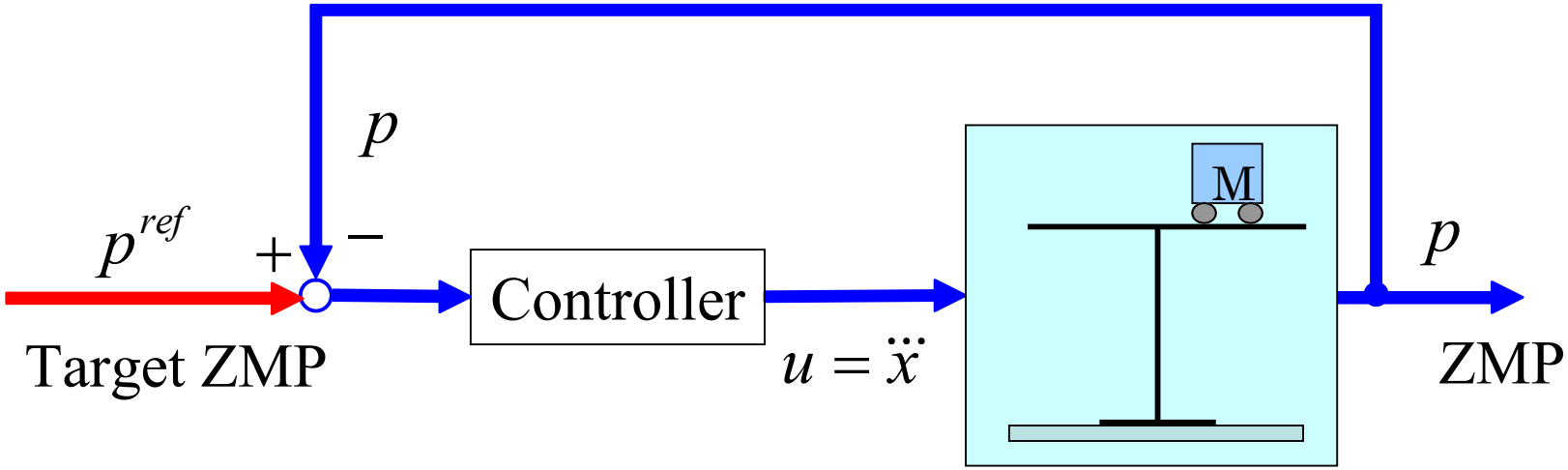


p

ZMP

【Walking pattern generation】
Calculate the cart trajectory to realize the given ZMP pattern

Servo tracking control of ZMP

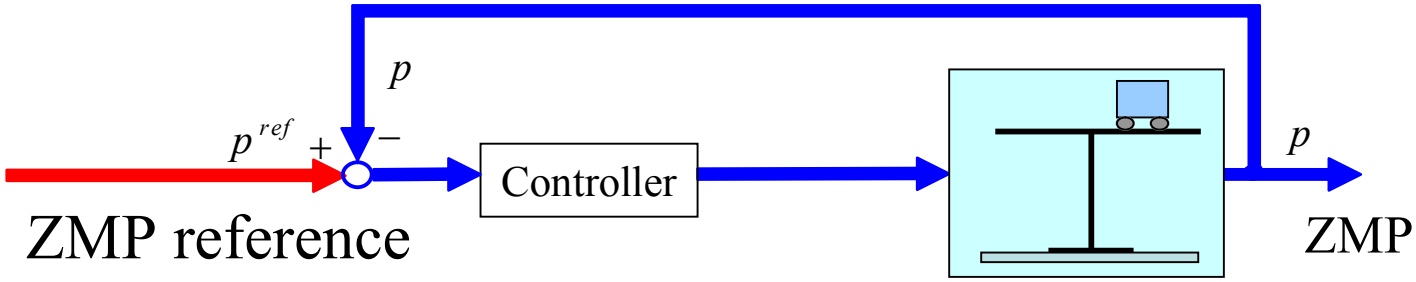


$$\frac{d}{dt}\begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u$$

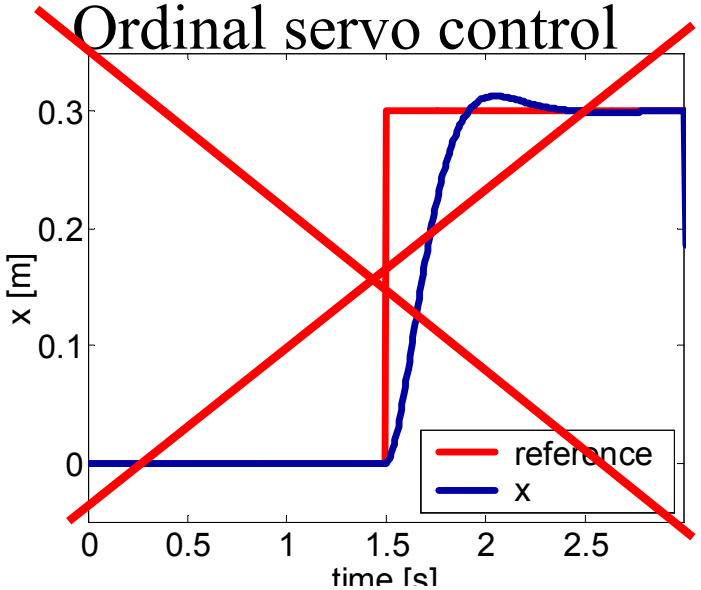
$$p = \begin{bmatrix} 1 & 0 & -\frac{z_h}{g} \end{bmatrix}\begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix}$$

Proper dynamics of
Cart-Table model

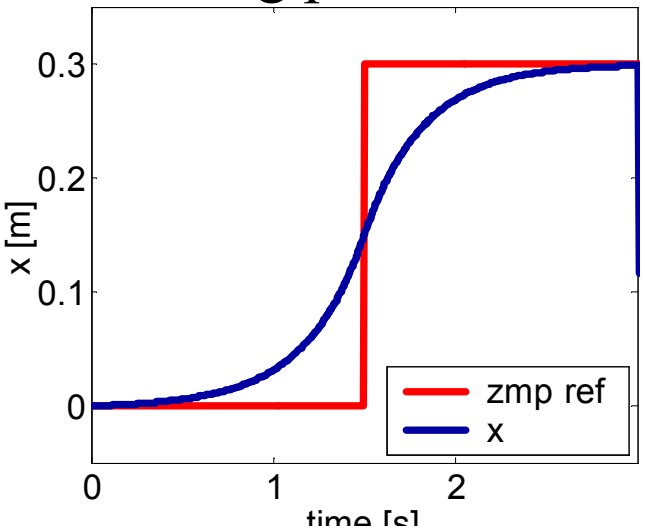
From ZMP reference to Cart motion



Ordinal servo control



Walking pattern



The cart must move before ZMP changes !

→Servo controller must use FUTURE information

The Preview Control

On a winding road, we steer a car by watching ahead,
by previewing the future reference.

- Concept and naming
  [Sheridan 1966]
- LQ optimal controller
  [Tomizuka and Rosenthal 1979]
  [Katayama et.al 1985]

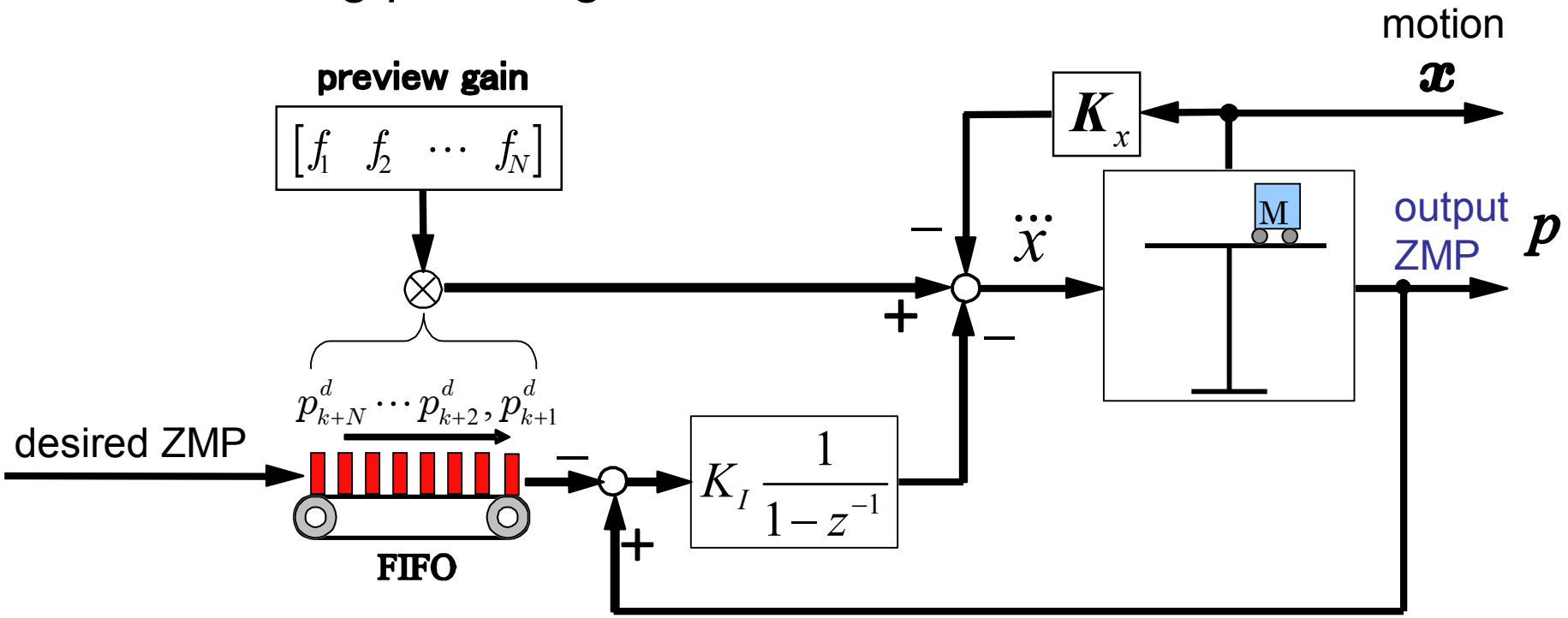
Control law

$$u_k = \underbrace{-K_x \boldsymbol{x}_k}_{\text{State feedback}} \underbrace{- K_I \sum_{i=0}^{k} (p_k - p_k^{ref})}_{\text{Accumulate ZMP error}} \underbrace{-[f_1, f_2, \cdots f_N] \begin{bmatrix} p_{k+1}^{ref} \\ \vdots \\ p_{k+N}^{ref} \end{bmatrix}}_{\text{Preview gain}}$$

Target ZMP of N-step future

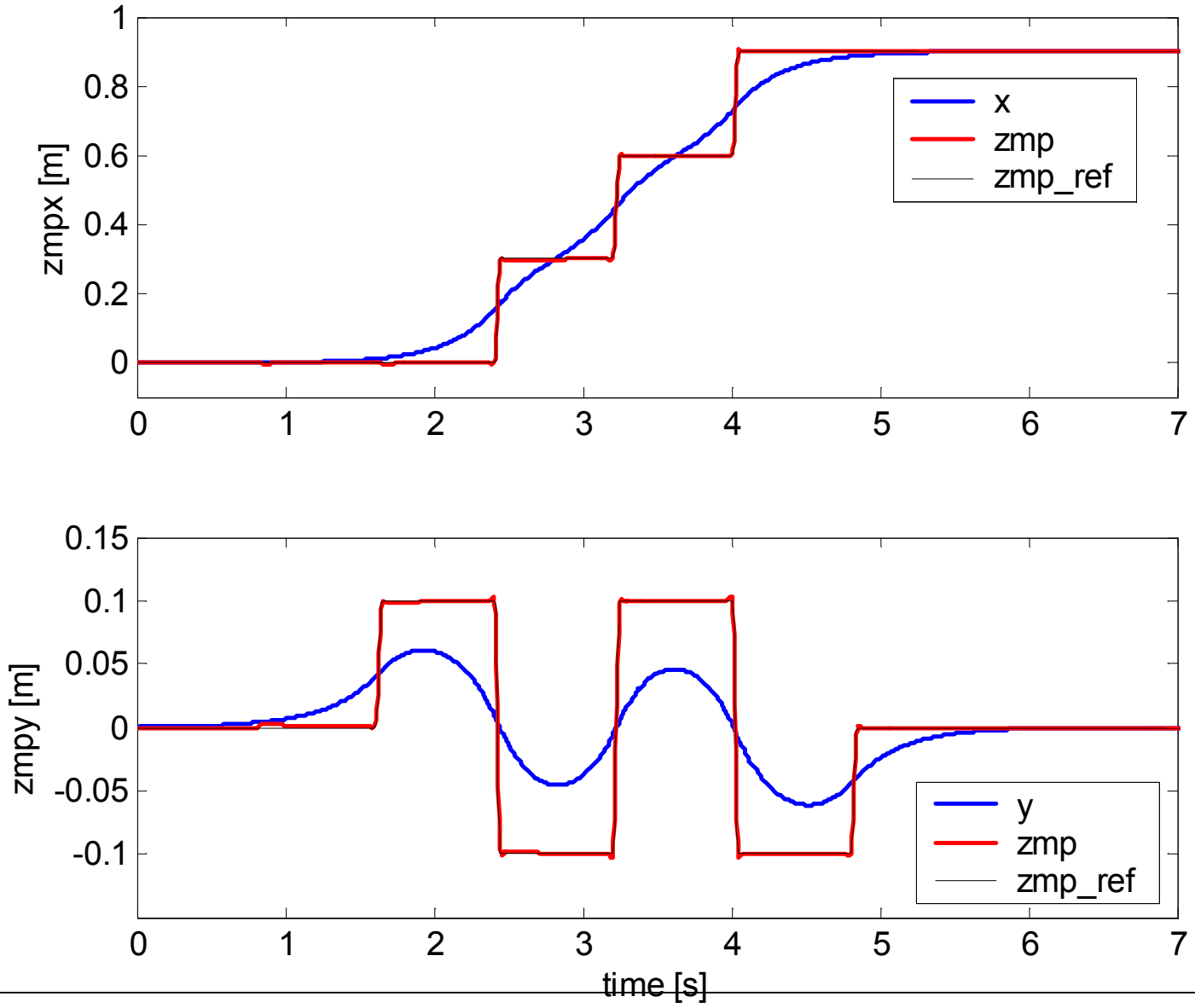
ZMP preview control [Kajita et al. ICRA2003]

- We can design a controller which minimizes the error between the desired ZMP and the output ZMP by applying the preview controller. This allows us to implement a real-time walking pattern generator.

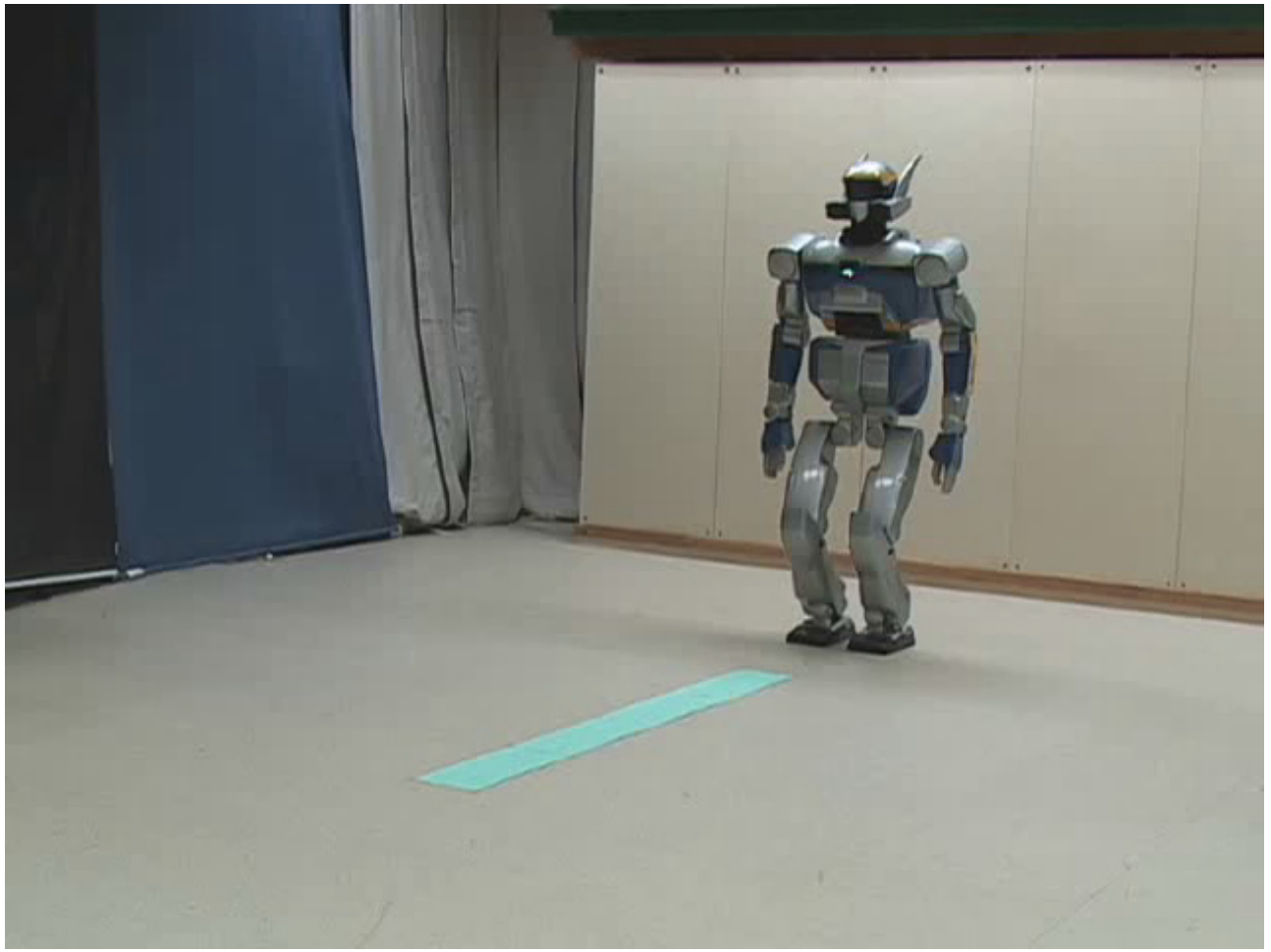


FIFO: First In First Out Buffer

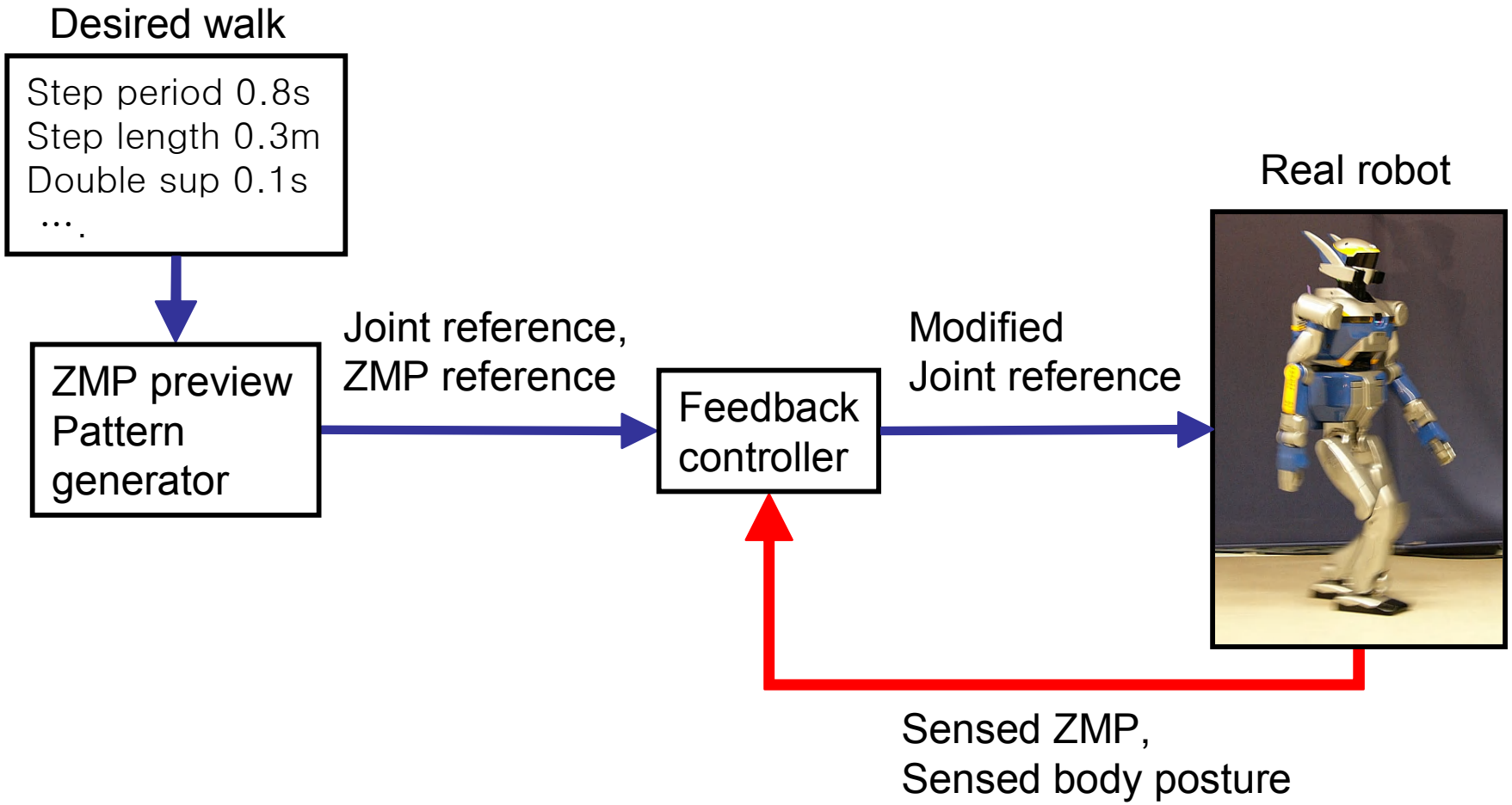
ZMP Tracking Example



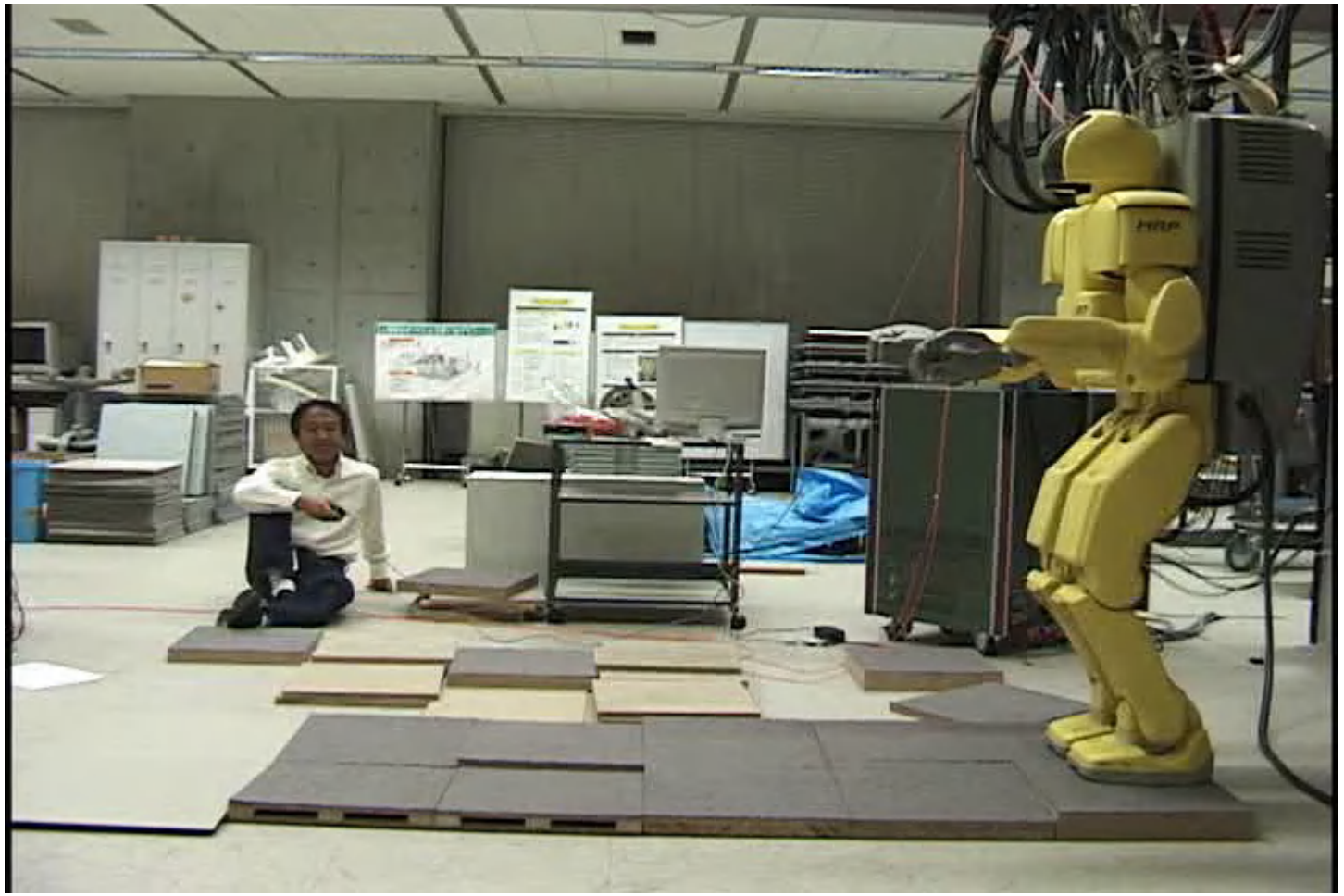
Experiment of HRP-2



Sensor feedback control



Terrain adaptations of HRP-1S



Terrain adaptation of HRP-2

Facts on the feedback control

- Without stabilization, our robot cannot walk.
- So far, our controller is not designed based on solid control theory. Thus we have not yet published the related paper.
- A good paper is recently published by some researchers.

  Choi, Kim, Oh and You, "Posture/Walking Control for Humanoid Robot Based on Kinematic Resolution of CoM Jacobian With Embedded Motion," IEEE Trans. Robotics, vol.23, issue 6, pp.1285-1293, 2007

Dance performance

Dance with European beat

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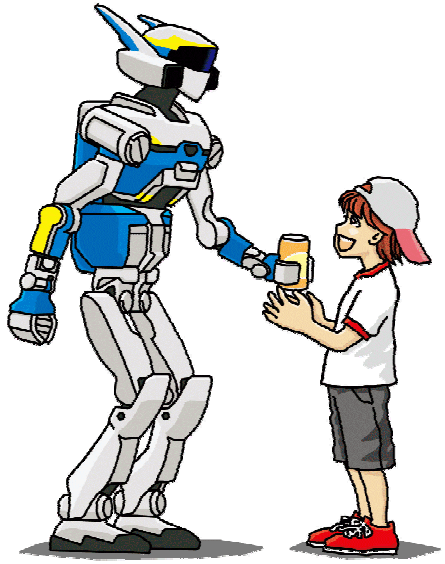


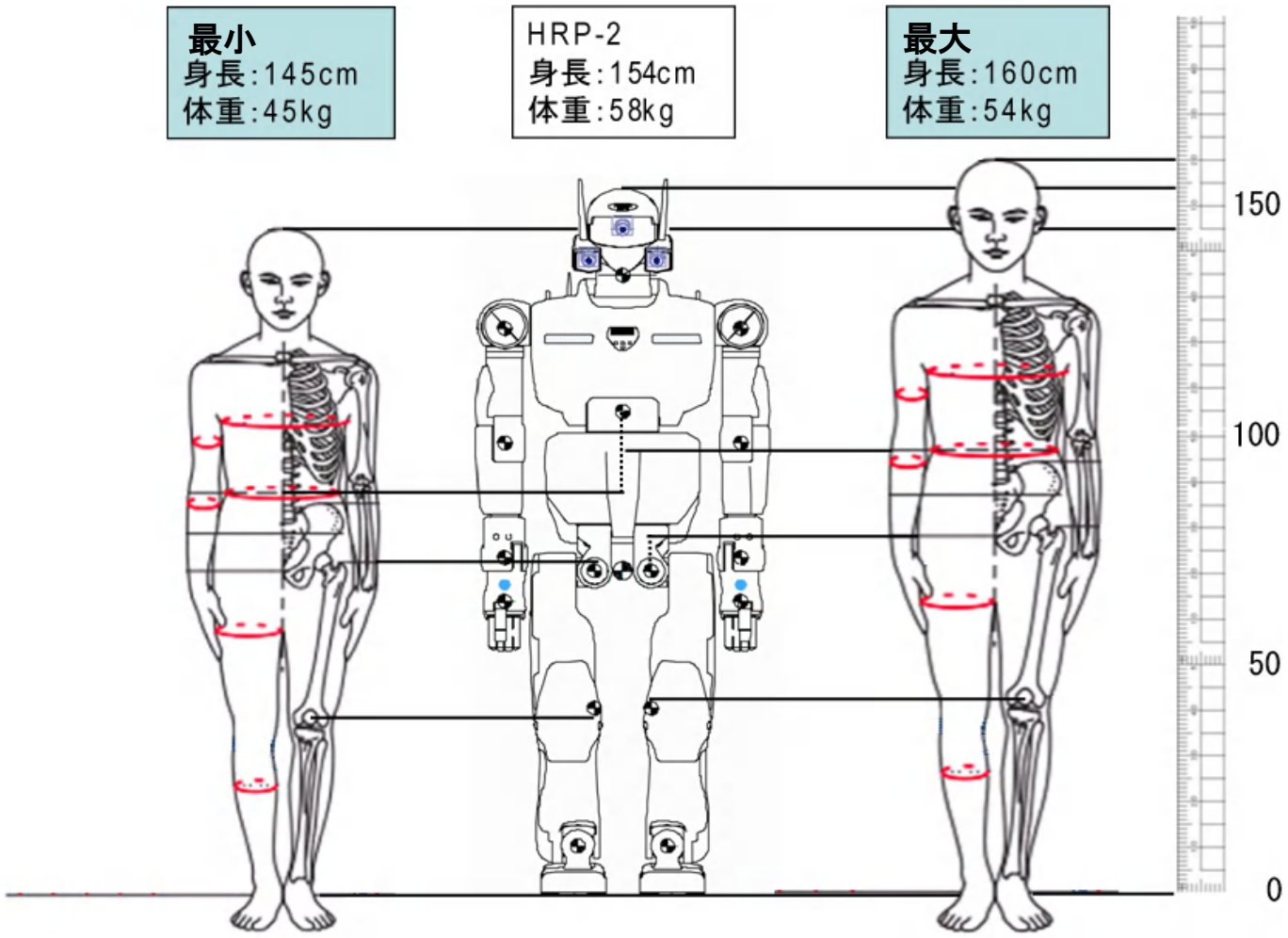
What's next?

HRP-2

HRP-3

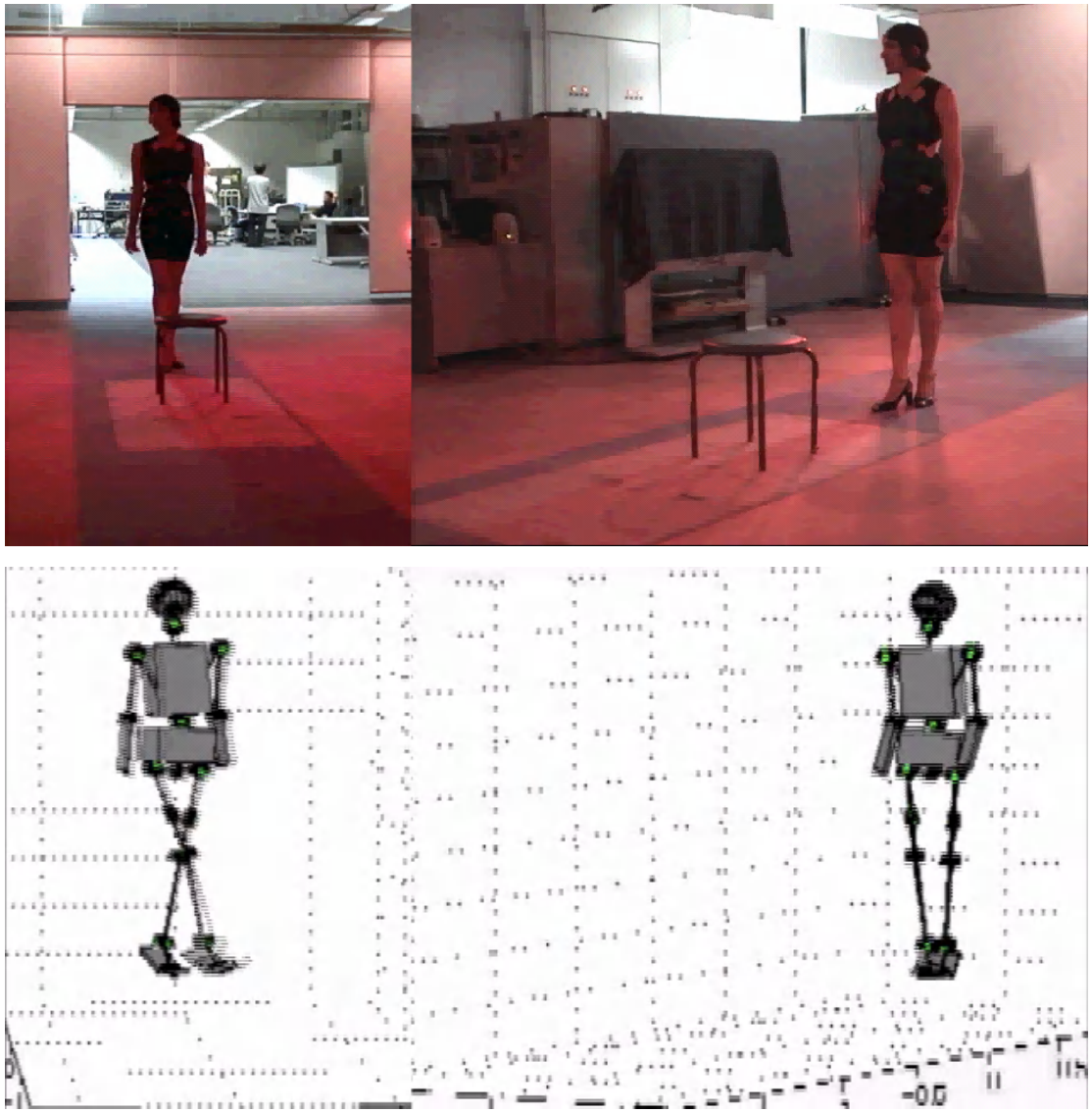
HRP-4

HRP-2 and average Japanese female



Database by
DHLC, AIST

To mimic a walk of mannequin



Schedule for HRP-4 development

2008

Spring

HRP-4L(leg part) hardware completion

Experiment and evaluation

Summer

Complete HRP-4 full-body model design

Winter

HRP-4 hardware completion

2009

Experiment and evaluation of HRP-4

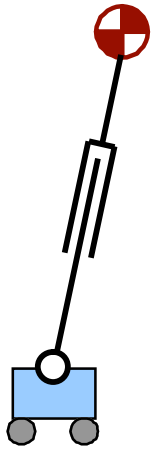
Spring

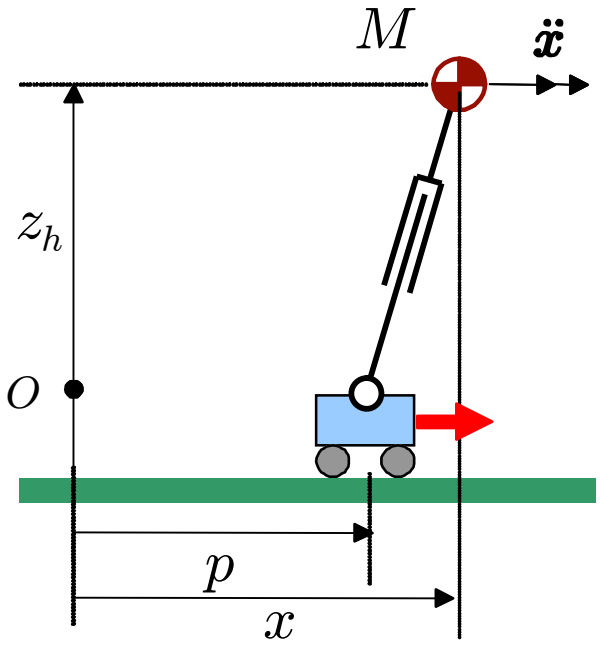
(Press release ?)

Thank you for kind attentions!

Carted-Pendulum Model

[Sugihara et al. ICRA2002]

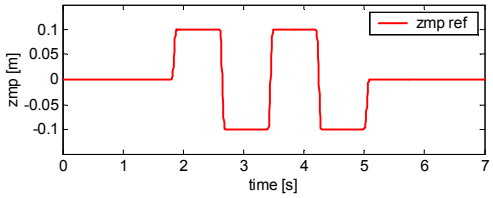




$$\ddot{x} = \frac{g}{z_h}(x - p)$$

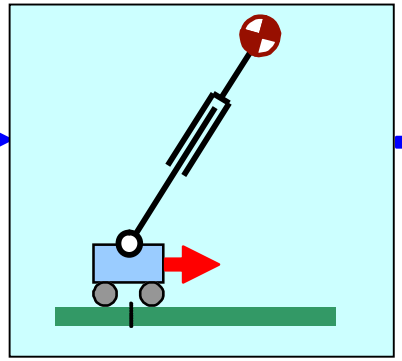
- The robot dynamics can be approximated by a pendulum on a mass-less running cart
- The dual of the cat-table model

Dual systems

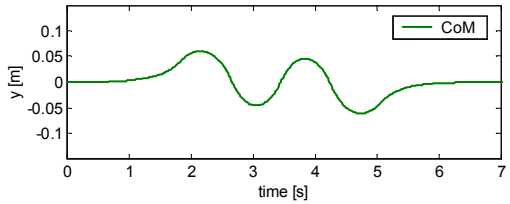


p

ZMP

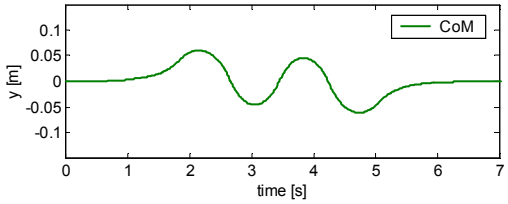


$$\ddot{x} = \frac{g}{z_h}(x - p)$$



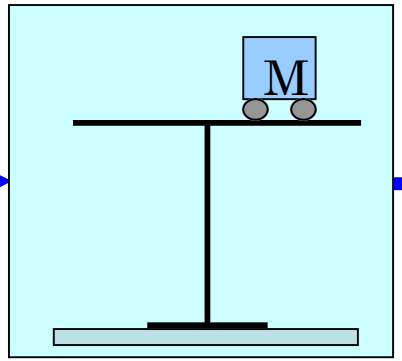
x

CoM

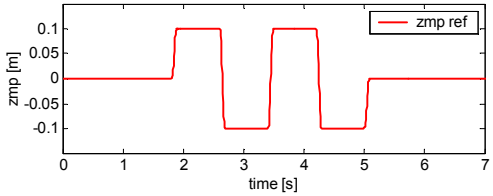


x

Cart trajectory



$$p = x - \frac{z_h}{g}\ddot{x}$$

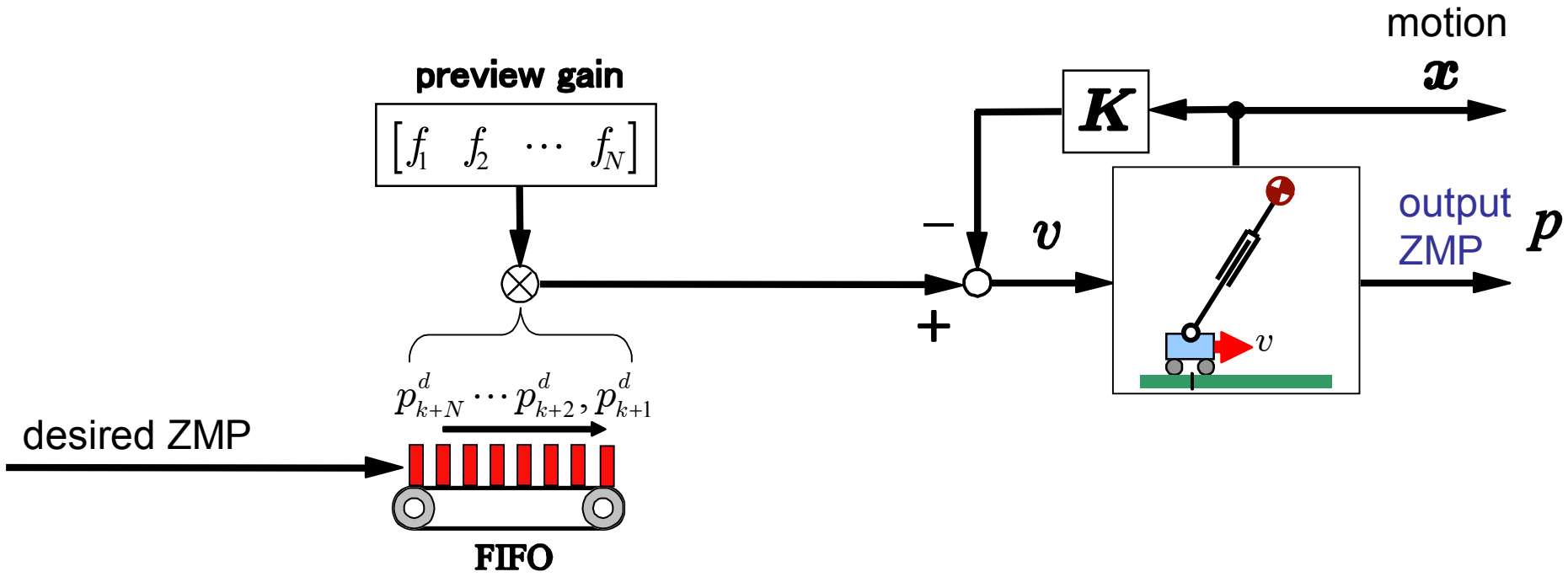


p

ZMP

ZMP preview control [Kajita et al. IROS2006]

- We can also design a ZMP preview controller using carted inverted pendulum.



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