

Humanoid Robots and biped locomotion



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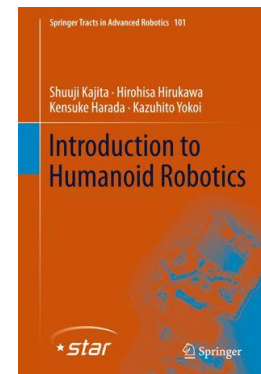
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Outline

- What is a Humanoid?
- Why Humanoid Robots?
- Challenges in Humanoid robotics
- Active vs Passive Locomotion
- Active Bipedal Locomotion
 - Humanoid Robot kinematics
 - Humanoid Robot Dynamics (Stability via ZMP)

REFERENCE MATERIAL

Kajita, S., Hirukawa, H., Harada, K., & Yokoi, K. (2014). *Introduction to humanoid robotics* (Vol. 101, p. 2014). Springer Berlin Heidelberg.



What is a Humanoid?

- Humanoid refers to any being whose body structure resembles that of a human: head, torso, legs, arms, hands.
- But it is also a robot made to resemble a human both in **appearance** and **behavior**.
- The difference between a **robot** and **android** is only skin-deep, looks exactly like humans on the outside, but with internal mechanics of humanoid robot.

Why Humanoid Robots?

- More rational reasons
 - They can work in human environment without a need to adapt themselves or to change the environment
 - Environment and tools are made for humans so are suitable for /humanoid robots
 - It is easier for a human being to interact with a humanoid than other robots

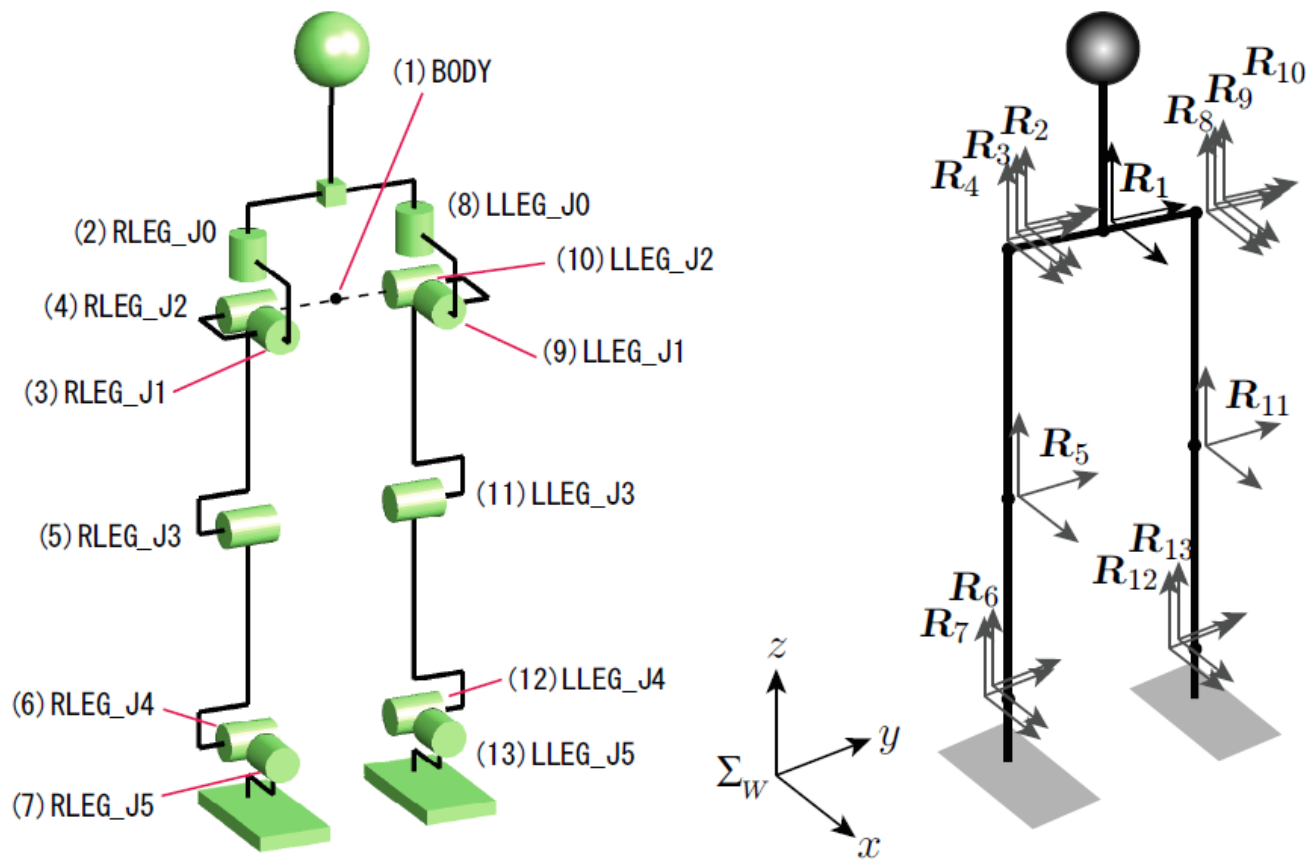
Challenges for Humanoid Robots

- Bipedal locomotion
 - Stable gait
 - Changing model during one/two feet support walking
 - Two legs, two arms, head, torso
- Hyper DOF system (>20)
 - Complex kinematics and dynamics
- Complex real-time control architecture

Active vs. Passive Locomotion

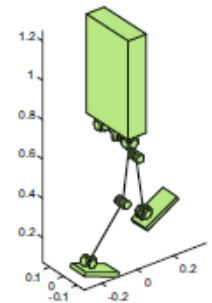
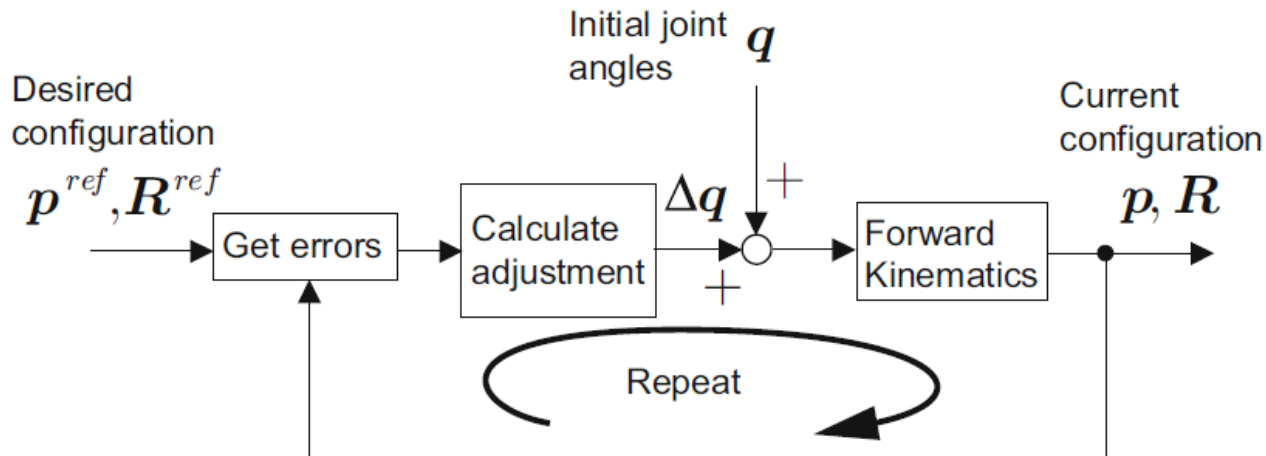
- Common humanoid (**ACTIVE**) uses all their DOF to perform the movement:
 - Continuous motor consumption (including arms)
 - Continuous motor control and synchronization
 - Extremely complex real-time control
- How is possible to reduce complexity?
(TOWARDS PASSIVE LOCOMOTION)
 - Reducing number of active DOF
 - Using energy of previous step to generate the next one
 - These actions reduce also the consumption
 - **Robot not fully controllable**

Kinematics of Humanoid Robots



Kinematics of Humanoid Robots (II)

- Numerical solution to Inverse Kinematics



Kinematics of Humanoid Robots (III)

- Newton-Raphson method

$$\delta \mathbf{p} = \mathbf{X}_p(\mathbf{q}, \delta \mathbf{q})$$

$$\delta \boldsymbol{\theta} = \mathbf{X}_\theta(\mathbf{q}, \delta \mathbf{q}).$$

$$\begin{bmatrix} \delta \mathbf{p} \\ \delta \boldsymbol{\theta} \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} & J_{13} & J_{14} & J_{15} & J_{16} \\ J_{21} & J_{22} & J_{23} & J_{24} & J_{25} & J_{26} \\ J_{31} & J_{32} & J_{33} & J_{34} & J_{35} & J_{36} \\ J_{41} & J_{42} & J_{43} & J_{44} & J_{45} & J_{46} \\ J_{51} & J_{52} & J_{53} & J_{54} & J_{55} & J_{56} \\ J_{61} & J_{62} & J_{63} & J_{64} & J_{65} & J_{66} \end{bmatrix} \delta \mathbf{q}.$$

$$\begin{bmatrix} \delta \mathbf{p} \\ \delta \boldsymbol{\theta} \end{bmatrix} = \mathbf{J} \delta \mathbf{q}.$$

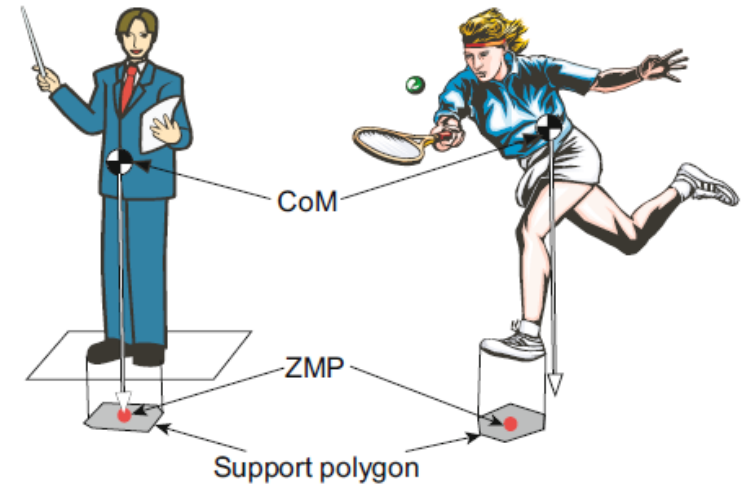
- We calculate the adjustment with the inverse

$$\delta \mathbf{q} = \lambda \mathbf{J}^{-1} \begin{bmatrix} \delta \mathbf{p} \\ \delta \boldsymbol{\theta} \end{bmatrix}.$$

Coefficient to stabilize the numerical computation

Bipedal Locomotion and ZMP

- **ZMP (Zero Moment Point)** specifies the point with respect to which dynamic reaction force at the contact of the foot with the ground does not produce any moment, i.e. the point where total inertia force equals 0 (zero).

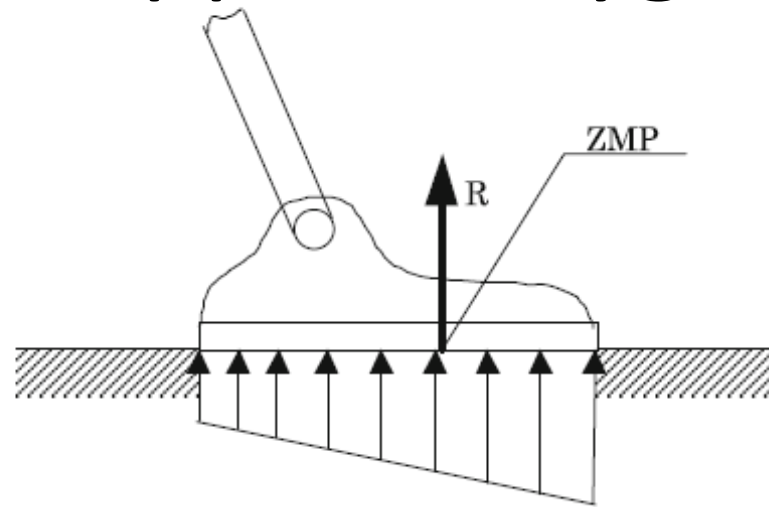


(a) A standing human

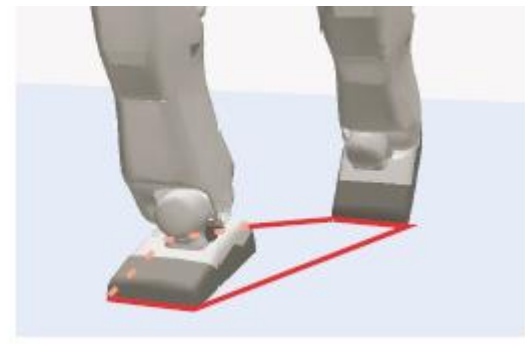
(b) A human in action

- **ZMP is the indicator** of the stability of the robot:
- The shadow depends on single or double support phase.

Support Polygon

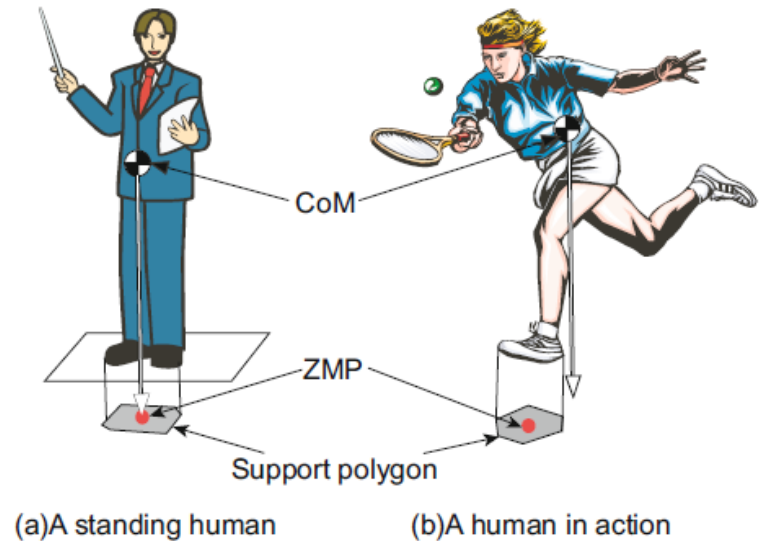


- Consider the region formed by enclosing all the contact points between the robot and the ground by using an elastic cord braid. We call this region as the **support polygon**.
- Mathematically the support polygon is defined as a convex hull, which is the smallest convex set including all contact points.



ZMP

- When a human stands on the ground, the ZMP coincides with the ground projection of CoM.
- A human can keep balance if the ground projection of CoM is included strictly inside of the support polygon.
- when a human moves dynamically the ground projection of CoM may exist outside the support polygon.
- However, the ZMP never exists outside the support polygon.

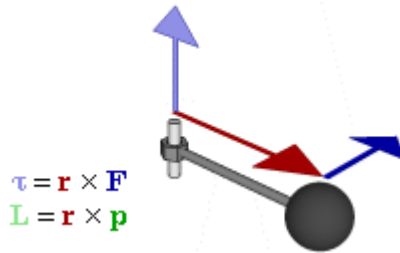


The ZMP always exists inside of the support polygon.

Moment of a force

- A **moment** is an expression involving the product of a distance and another physical quantity, and in this way it accounts for how the physical quantity is located or arranged

$$\vec{\tau} = \vec{r} \times \vec{F}$$



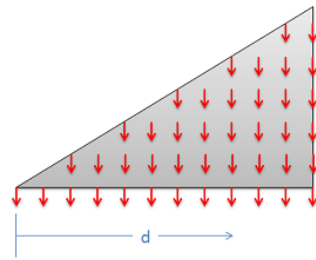
The moment is the cross product of a force vector with the position vector to its point of application

The moment vector is perpendicular to the plane formed by the position vector and the force vector (e.g., imagine drawing them tail-to-tail)

Right Hand Rule: curl fingers from r to F , thumb points along torque.

Moment Integral

- The Moment Integral uses the **distance** from the center axis or point to calculate the moment. Moment integrals are useful in calculating the equivalent point load, the centroid, and the center of mass of an object, because on each of these we need to sum up the moments, which is equal to the force (F) times the moment arm (d).



$$\text{Total Moment} = \sum M$$

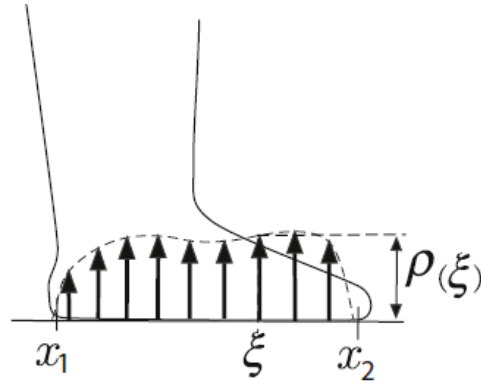


$$\text{Total Moment} = \sum F * d$$

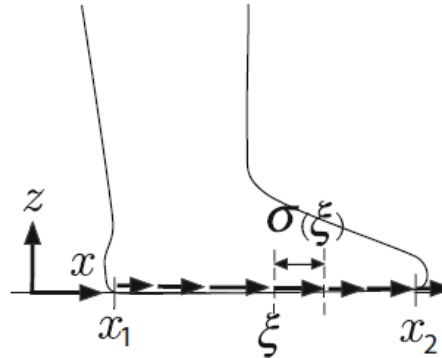
$$\text{first area moment integral} = \int_A F * d$$

http://adaptivemap.ma.psu.edu/websites/A2_moment_integrals/moment_integrals/momentintegrals.html

ZMP in 2D



Vertical Force



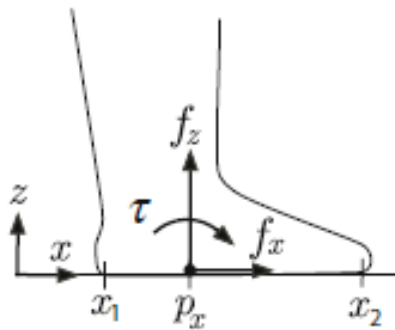
Horizontal force

The force f_x and f_z and the moment $\tau(p_x)$ at the point p_x are expressed as follows:

$$f_x = \int_{x_1}^{x_2} \sigma(\xi) d\xi$$

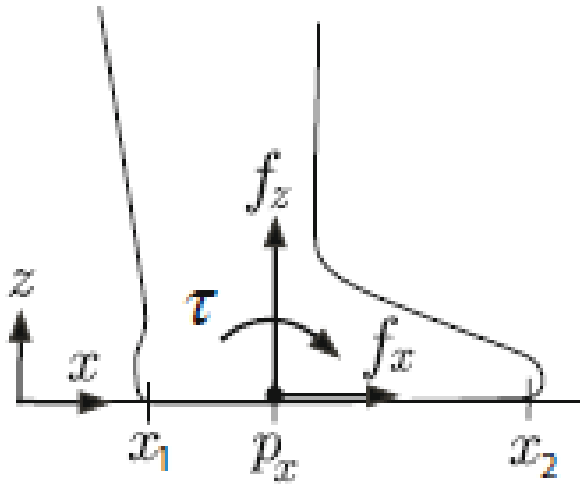
$$f_z = \int_{x_1}^{x_2} \rho(\xi) d\xi$$

$$\tau(p_x) = - \int_{x_1}^{x_2} (\xi - p_x) \rho(\xi) d\xi.$$



ZMP in 2D (2)

Considering the point where $p(x)$ becomes zero



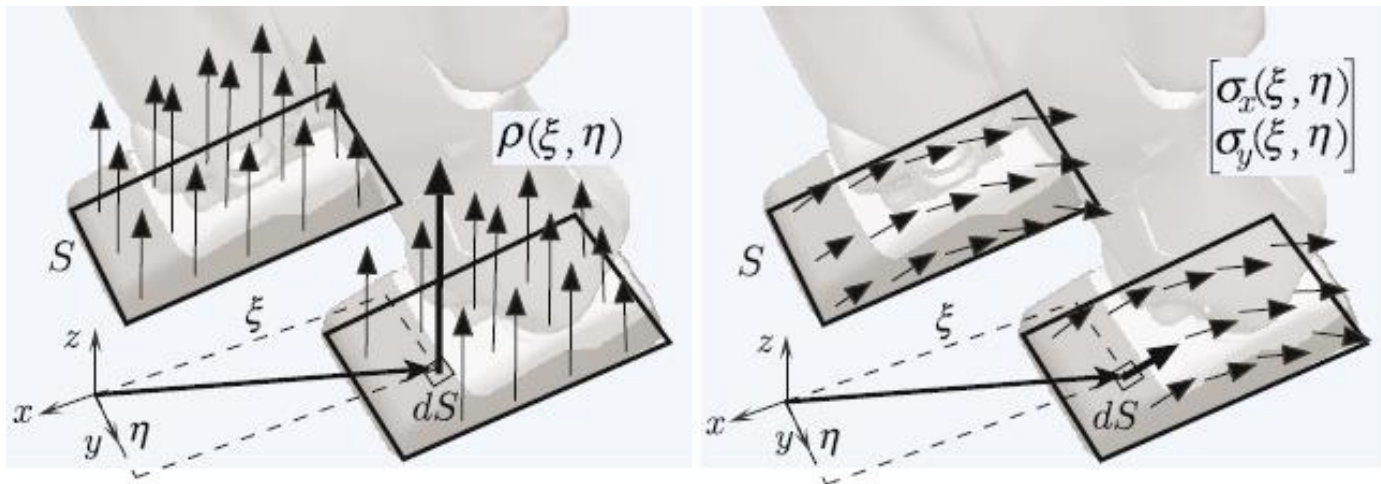
$$p_x = \frac{\int_{x_1}^{x_2} \xi \rho(\xi) d\xi}{\int_{x_1}^{x_2} \rho(\xi) d\xi}.$$

Thus $p(x)$ is the center of pressure and is the **ZMP** previously defined

ZMP in 3D

- Let $\mathbf{r}=[\xi \ \eta \ 0]^T$ the position vector defined on the ground with a vertical component $\rho=(\xi,\eta)$. The sum of the vertical component is defined as follows:

$$\mathbf{f}_z = \int_S \rho(\xi,\eta) dS,$$



ZMP in 3D (vertical component)

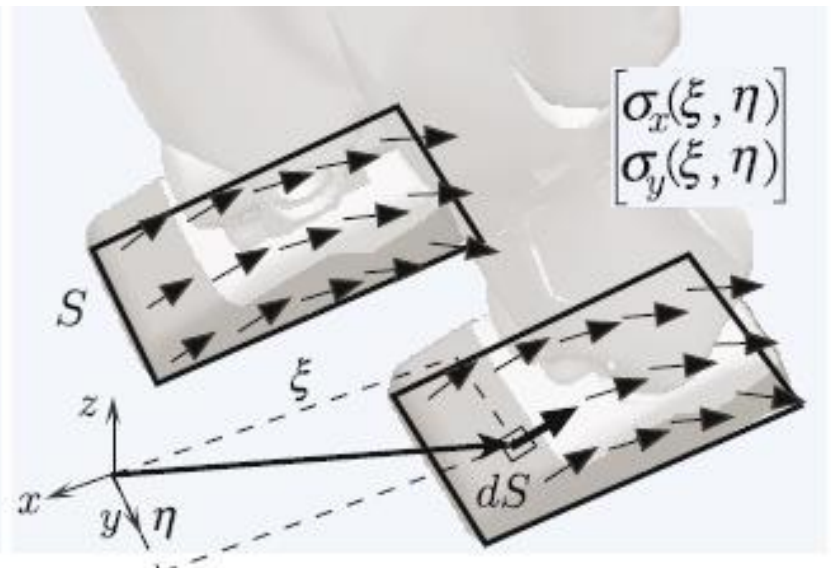
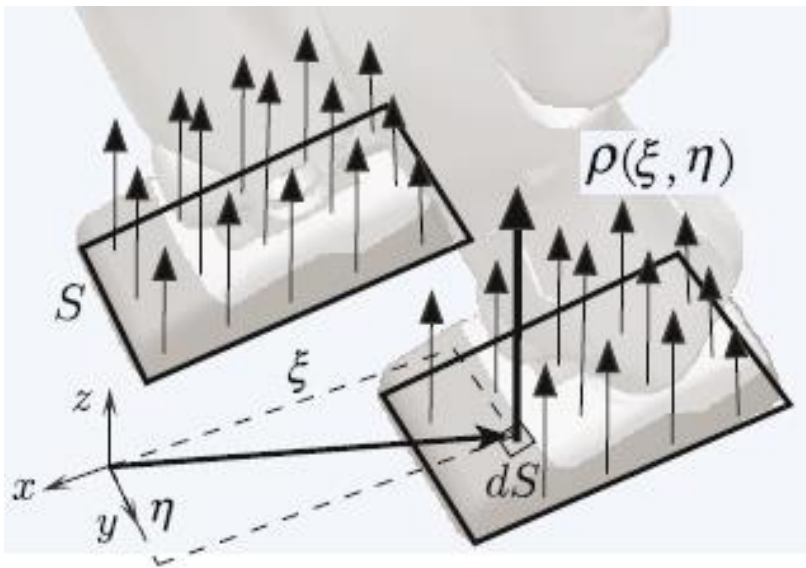
\int_S denotes the integration area at the contact point. The moment $\tau_n(p)$ is calculated as:

$$\tau_n(p) \equiv [\tau_{nx} \ \tau_{ny} \ \tau_{nz}]^T$$

$$\tau_{nx} = \int_S (\eta - p_y) \rho(\xi, \eta) dS$$

$$\tau_{ny} = - \int_S (\xi - p_x) \rho(\xi, \eta) dS$$

$$\tau_{nz} = 0.$$



ZMP in 3D (vertical component)

Assuming as for the 2D case:

$$\tau_{nx} = 0$$

$$\tau_{ny} = 0$$

The point where the moment of the vertical component of the ground reaction force becomes zero can be expressed as:

$$p_x = \frac{\int_S \xi \rho(\xi, \eta) dS}{\int_S \rho(\xi, \eta) dS}$$
$$p_y = \frac{\int_S \eta \rho(\xi, \eta) dS}{\int_S \rho(\xi, \eta) dS}.$$

p is the center of pressure or ZMP

ZMP in 3D (horizontal component)

$$\boldsymbol{\tau}_t(\mathbf{p}) \equiv [\tau_{tx} \ \tau_{ty} \ \tau_{tz}]^T$$

$$\tau_{tx} = 0$$

$$\tau_{ty} = 0$$

$$\tau_{tz} = \int_S \{(\xi - p_x)\sigma_y(\xi, \eta) - (\eta - p_y)\sigma_x(\xi, \eta)\} dS.$$

$$f_x = \int_S \sigma_x(\xi, \eta) dS$$

$$f_y = \int_S \sigma_y(\xi, \eta) dS.$$

These equations mean that the **horizontal ground reaction forces** generate the **vertical component** of the moment.



ZMP in 3D (horizontal component)

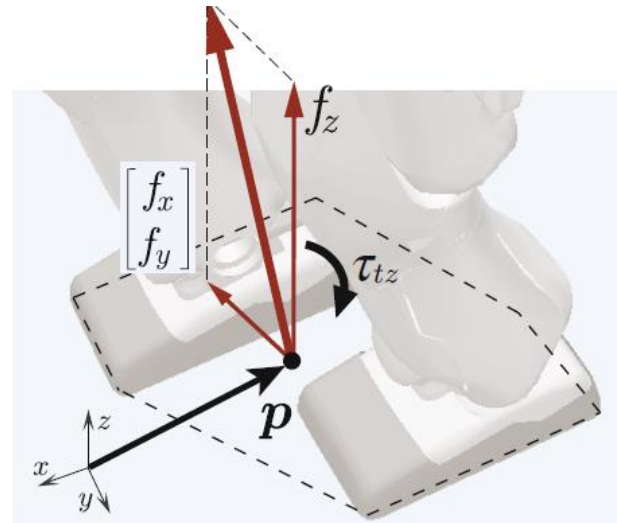
The ground reaction forces distributed over the surface of the sole can be replaced by the force

$$\mathbf{f} = [f_x \ f_y \ f_z]^T$$

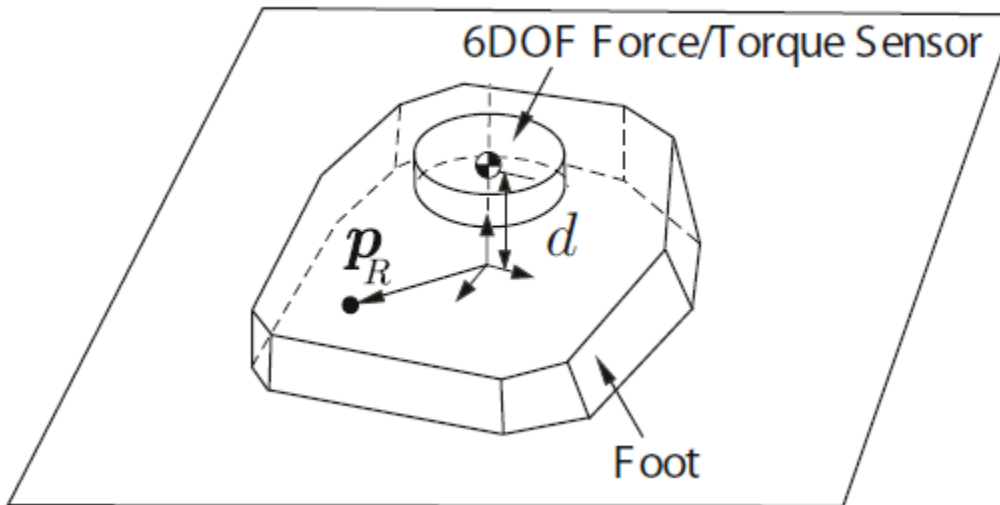
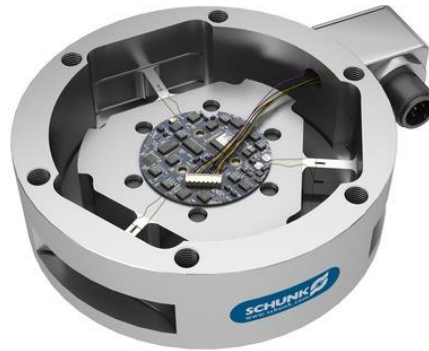
and the moment :

$$\begin{aligned}\boldsymbol{\tau}_p &= \boldsymbol{\tau}_n(\mathbf{p}) + \boldsymbol{\tau}_t(\mathbf{p}) \\ &= [0 \ 0 \ \tau_{tz}]^T,\end{aligned}$$

Thus the ZMP is defined as **the point where the horizontal component of the moment of the ground reaction forces becomes zero** for 3D cases.



Force sensors



Measurement of ZMP

- **The ZMP of each foot** considering the reaction force between either one of the feet and the ground, and the ZMP considering the reaction force between both feet and the ground.
- During the double support phase, these two ZMPs becomes different.

Measurement of ZMP (II)

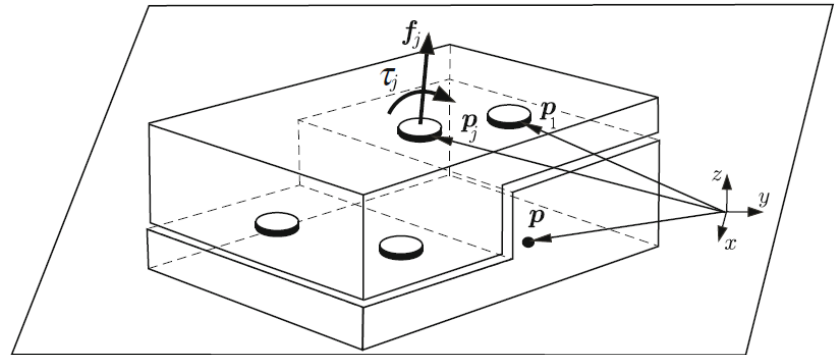
- Let us assume that, at the points \mathbf{p}_j ($j = 1, \dots, N$) with respect to the reference coordinate system, the forces \mathbf{f}_j and moments $\boldsymbol{\tau}_j$ are measured. Here, the moment about the point $\mathbf{p} = [p_x \ p_y \ p_z]$ is

$$\boldsymbol{\tau}(\mathbf{p}) = \sum_{j=1}^N (\mathbf{p}_j - \mathbf{p}) \times \mathbf{f}_j + \boldsymbol{\tau}_j$$

$$\mathbf{f}_j = [f_{jx} \ f_{jy} \ f_{jz}]^T$$

$$\boldsymbol{\tau}_j = [\tau_{jx} \ \tau_{jy} \ \tau_{jz}]^T$$

$$\mathbf{p}_j = [p_{jx} \ p_{jy} \ p_{jz}]^T$$



Measurement of ZMP (III)

$$\vec{\tau} = \sum_{j=1}^N \vec{p}_j - \vec{p} \times \vec{f}_j + \vec{\tau}_j = 0$$

Vector product

$$\begin{pmatrix} \hat{x} & \hat{y} & \hat{z} \\ i & j & k \\ p_x & p_y & p_z \\ f_x & f_y & f_z \end{pmatrix}$$

$$(p_y f_z - p_z f_y) \hat{x}$$

$$(p_z f_x - p_x f_z) \hat{y}$$

Setting the *x and y* component to zero

$$\tau_x = 0 \quad \tau_y = 0$$

$$\tau_x = \sum_{j=1}^N \{ [(p_{jy} - p_y) f_{jz} - (p_{jz} - p_z) f_{jy}] + \tau_{jx} \} = 0$$

$$\tau_y = \sum_{j=1}^N \{ [(p_{jz} - p_z) f_{jx} - (p_{jx} - p_x) f_{jz}] + \tau_{jy} \} = 0$$

Solving by $p_x p_y$

$$p_x = \frac{\sum_{j=1}^N \{ -\tau_{jy} - (p_{jz} - p_z) f_{jx} + p_{jx} f_{jz} \}}{\sum_{j=1}^N f_{jz}}$$

$$p_y = \frac{\sum_{j=1}^N \{ \tau_{jx} - (p_{jz} - p_z) f_{jy} + p_{jy} f_{jz} \}}{\sum_{j=1}^N f_{jz}}$$

Basic equations for position of ZMP

Measurement of ZMP (IV)

(contact between one foot and the ground)

- The ground reaction force applied to the sole is transmitted to the sensor mount through rubber bushes and dampers.
- A 6 axis force/torque sensor is attached at the sensor mount, and the force is transmitted to the ankle of the robot through this sensor
- A 6 axis force/torque sensor is coordinated to simultaneously measure the force $\mathbf{f} = [f_x, f_y, f_z]$ and the moment $\boldsymbol{\tau} = [\tau_x \tau_y \tau_z]$ applied from outside the robot.

Measurement of ZMP (V)

(contact between one foot and the ground)

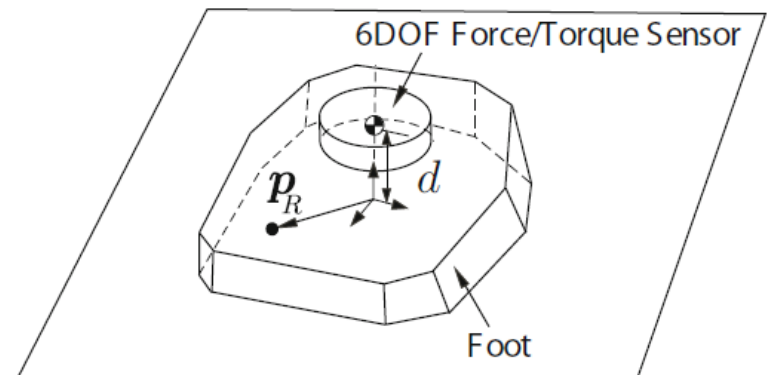
- Let the position of the ZMP in the right and the left foot be \mathbf{p}_R and \mathbf{p}_L
- The position of the ZMP (for the right foot) can be obtained as:

$$p_{Rx} = (-\tau_{1y} - f_{1x}d)/f_{1z}$$

$$p_{Ry} = (\tau_{1x} - f_{1y}d)/f_{1z}$$

$$\mathbf{p}_R = [p_{Rx} \ p_{Ry} \ p_{Rz}]^T$$

$$\mathbf{p}_1 = [0 \ 0 \ d]^T .$$



Measurement of ZMP (VI)

(both feet contact)

The position of the ZMP of each foot can be obtained as \mathbf{p}_R and \mathbf{p}_L . The ground reaction forces \mathbf{f}_R and \mathbf{f}_L are also obtained from the sensor information.

The **ZMP** in the case where both feet are **in contact with the ground** (using the basic equation for the ZMP computation) can be obtained as:

$$p_x = \frac{p_{Rx} f_{Rz} + p_{Lx} f_{Lz}}{f_{Rz} + f_{Lz}}$$

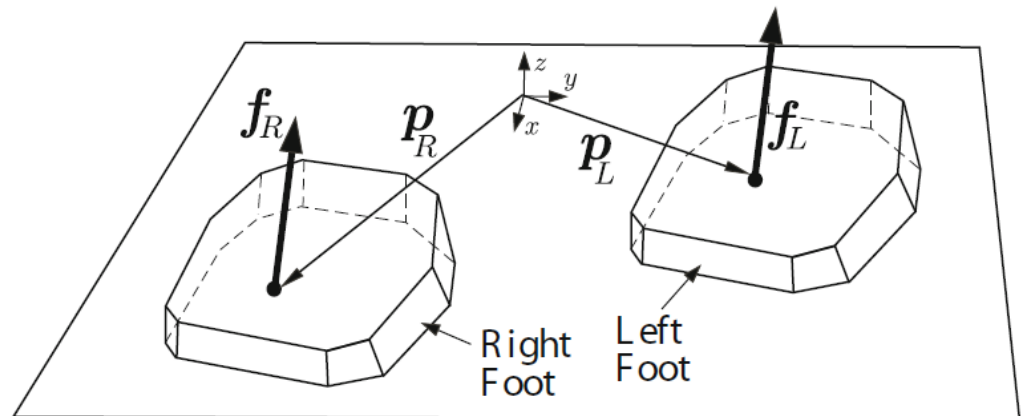
$$p_y = \frac{p_{Ry} f_{Rz} + p_{Ly} f_{Lz}}{f_{Rz} + f_{Lz}}$$

$$\mathbf{f}_R = [f_{Rx} \ f_{Ry} \ f_{Rz}]^T$$

$$\mathbf{f}_L = [f_{Lx} \ f_{Ly} \ f_{Lz}]^T$$

$$\mathbf{p}_R = [p_{Rx} \ p_{Ry} \ p_{Rz}]^T$$

$$\mathbf{p}_L = [p_{Lx} \ p_{Ly} \ p_{Lz}]^T$$




Measurement of ZMP (VII)

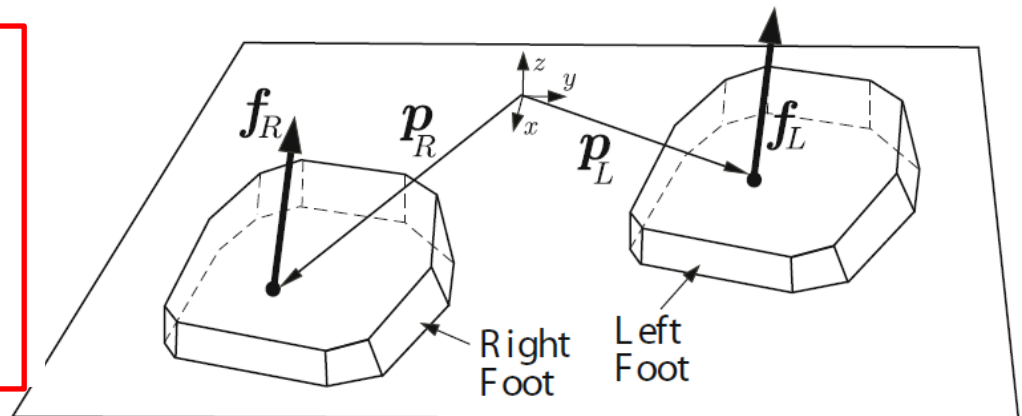
(both feet contact)

During the single support phase, since the vertical component of the ground reaction force becomes zero, the ZMP coincides with the ZMP of the supporting foot.

$$[p_x \ p_y \ p_z]^T = \begin{cases} [p_{Rx} \ p_{Ry} \ p_{Rz}]^T & \text{for support of right foot} \\ [p_{Lx} \ p_{Ly} \ p_{Lz}]^T & \text{for support of left foot.} \end{cases}$$

Considering the balance of a humanoid robot, we can use the following equations taking both feet into account regardless of the supporting foot.


$$p_x = \frac{p_{Rx} f_{Rz} + p_{Lx} f_{Lz}}{f_{Rz} + f_{Lz}}$$
$$p_y = \frac{p_{Ry} f_{Rz} + p_{Ly} f_{Lz}}{f_{Rz} + f_{Lz}}$$



Biped walking

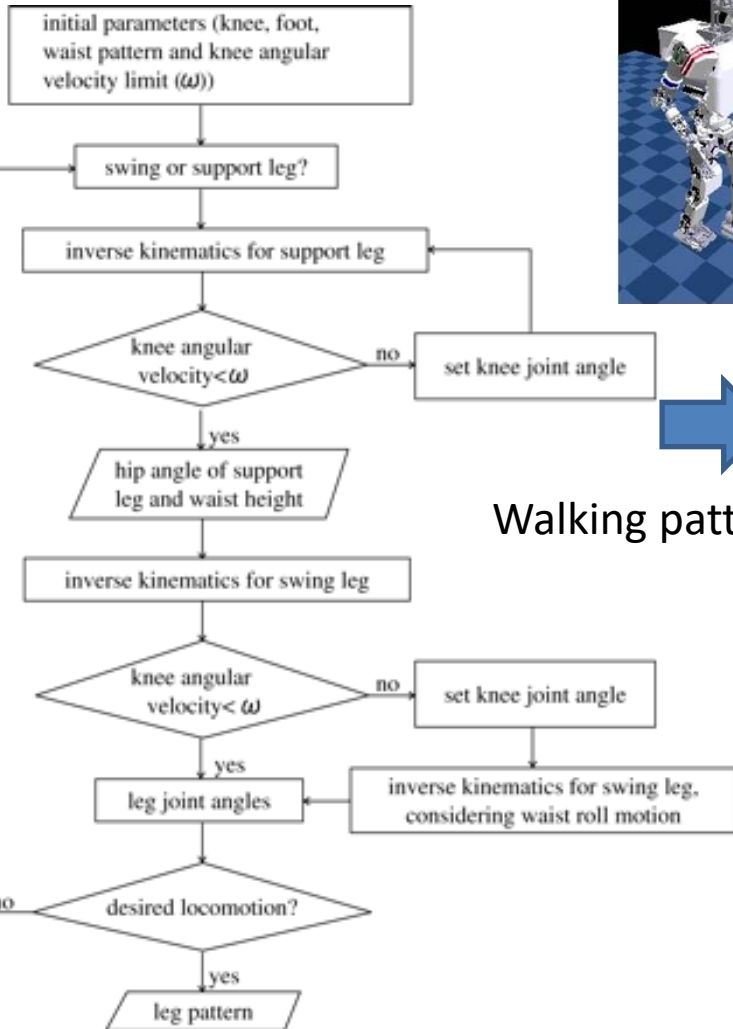
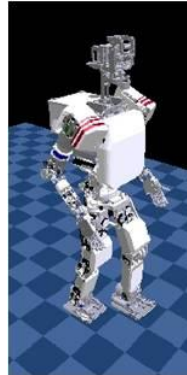
- There exist two kind of walking, namely, static walking and dynamic walking
 - In “dynamic walking”, there exist periods when the projection of the center of mass leaves the support polygon (human feet are too small with respect to the height of center of mass to perform static walking)
 - In “static walking”, the projection of the center of mass never leaves the support polygon during the walking

Pattern Generation

- A set of time series of joint angles for desired walking is called a *walking pattern*, and to create it, it is used a *walking pattern generator*
- In an ideal situation, biped walking can be realized just by giving a walking pattern to an actual robot
- A humanoid proportion and mass distribution tends to quickly amplify the posture error to an unstable level. To suppress this, we need the second software, which modifies the walking pattern by using gyros, accelerometers, force sensors and other devices. This is called a *stabilizer*

How to realize biped walking

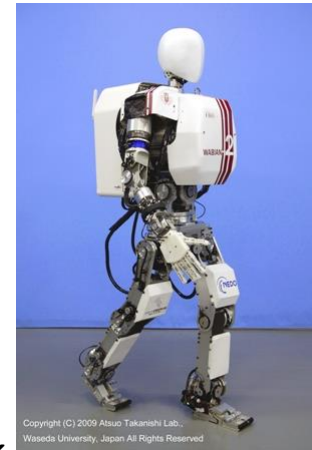
Pattern Generator Steps



Walking pattern

Stabilizer

Sensors feedback



- A humanoid proportion and mass distribution tends to quickly amplify the posture error to an unstable level.
 - To suppress this, it is needed a second software, which modifies the walking pattern by using force sensors and other devices. This is called a *stabilizer*

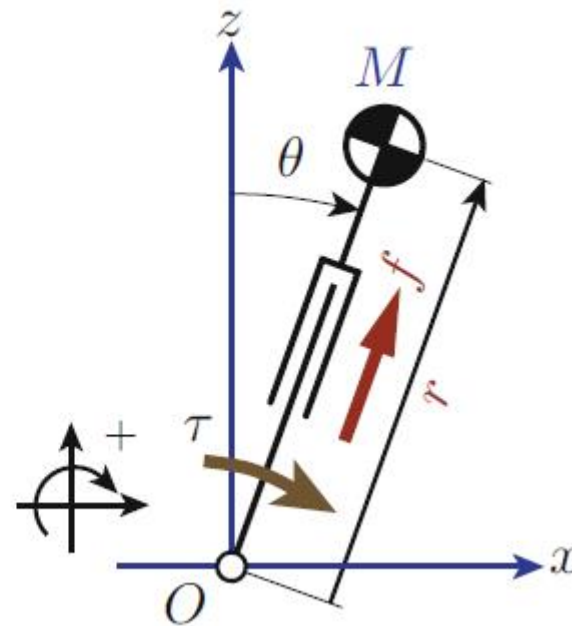
Stabilization mechanism

We make three assumptions as coarse-graining on a humanoid robot:

- 1) we assume that all the mass of the robot is concentrated at its center of mass (CoM).
- 2) we assume that the robot has massless legs, whose tips contact the ground at single rotating joints.
- 3) we only consider the forward/backward and the up/down motions of the robot, neglecting lateral motion.

In other words, we assume the robot motion is constrained to the *sagittal plane* defined by the axis of walking direction and vertical axis. With these assumptions, we model a robot as a **2D inverted pendulum**

Two dimensional inverted pendulum



The inputs of the pendulum are the torque τ and the pivot at the kick force f at the prismatic joint along the leg. The dynamics of the pendulum is as follows:

$$\begin{aligned} r^2 \ddot{\theta} + 2r\dot{r}\dot{\theta} - gr \sin \theta &= \tau/M \\ \ddot{r} - r\dot{\theta}^2 + g \cos \theta &= f/M. \end{aligned}$$

Behavior of the linear inverted pendulum

- While the vertical component of the f is canceled by gravity, the horizontal component is $M\ddot{x} = f \sin \theta$.

Applying different forces we get different behaviors:

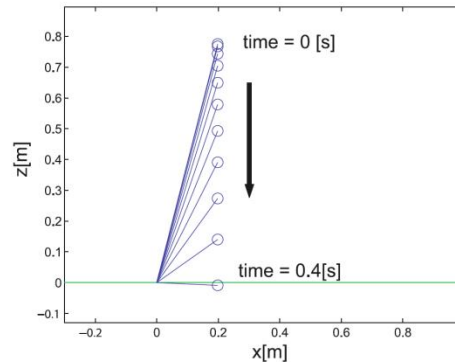


Applying the right force we obtain:

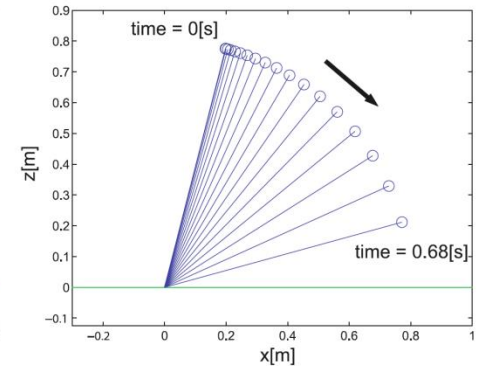
$$M\ddot{x} = \frac{Mg}{\cos \theta} \sin \theta = Mg \tan \theta = Mg \frac{x}{z}$$



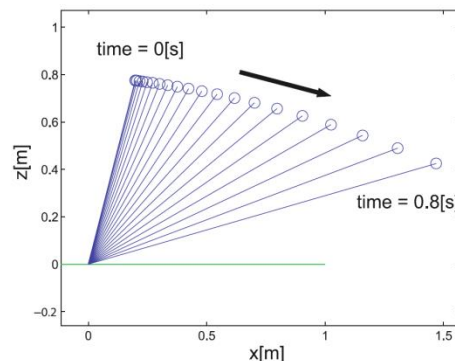
$$\ddot{x} = \frac{g}{z} x.$$



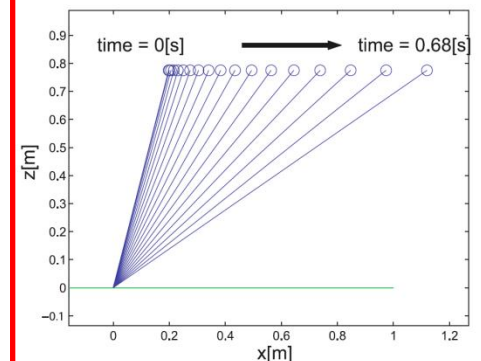
(a) $f = 0$: Free fall of CoM



(b) $f = Mg \cos \theta - Mr\dot{\theta}^2$: Fall down with constant leg length



(c) $f = Mg$: Fall down and acceleration



(d) $f = Mg / \cos \theta$: CoM accelerates while keeping the initial height

ZMP and COM

- Based on knowledge of the joint trajectories or the center of mass trajectory we would like to calculate the ZMP position.
- For a desired ZMP position we could find the necessary joint trajectories or the required center of mass trajectory. The center of mass – ZMP relationship is shown below

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

where, x, z gives the CoM of the inverted pendulum and p is the ZMP

