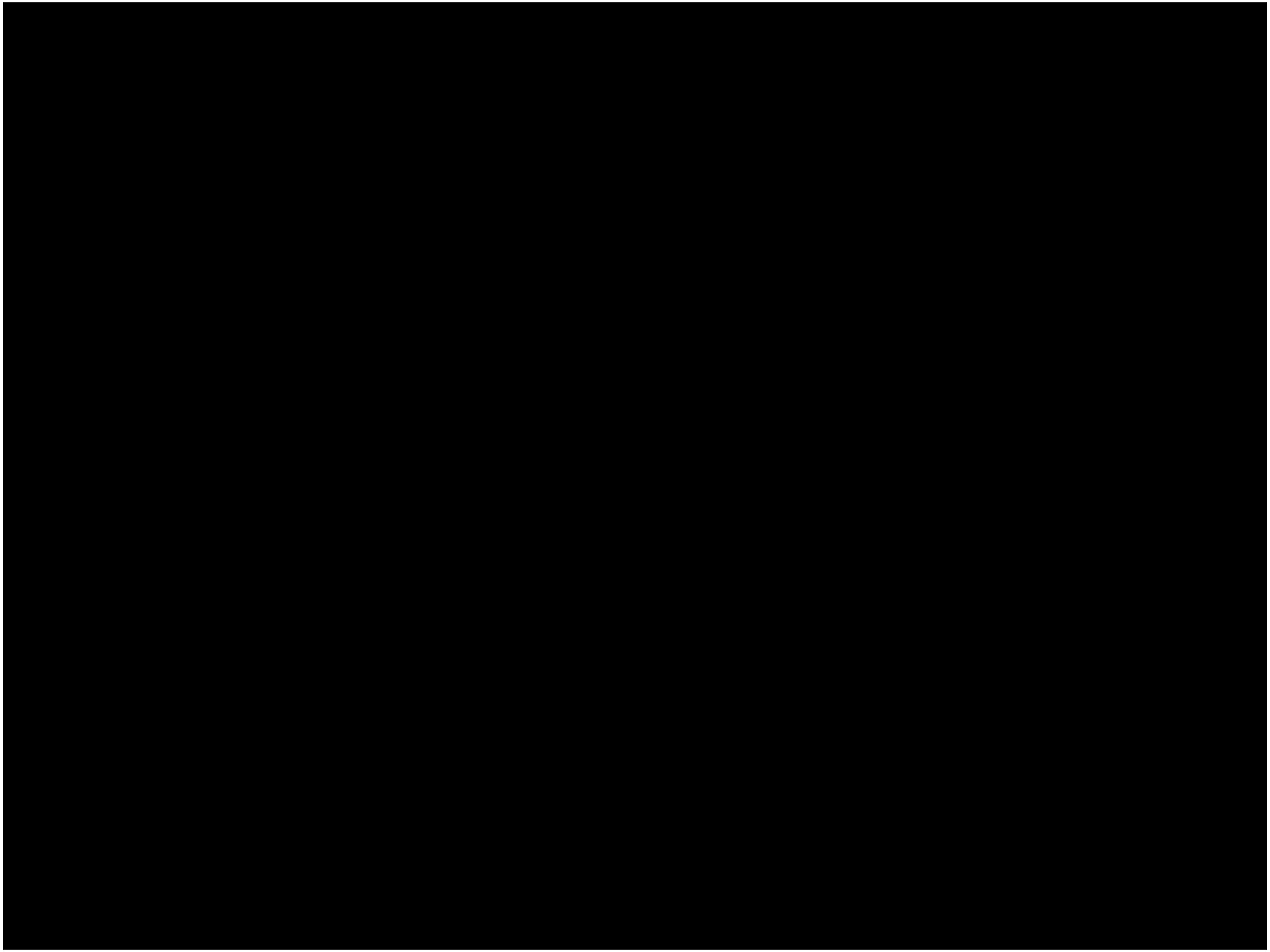
Bipedal Locomotion Planning Based on Divergent Component of Motion(DCM)

Legged Robots Course

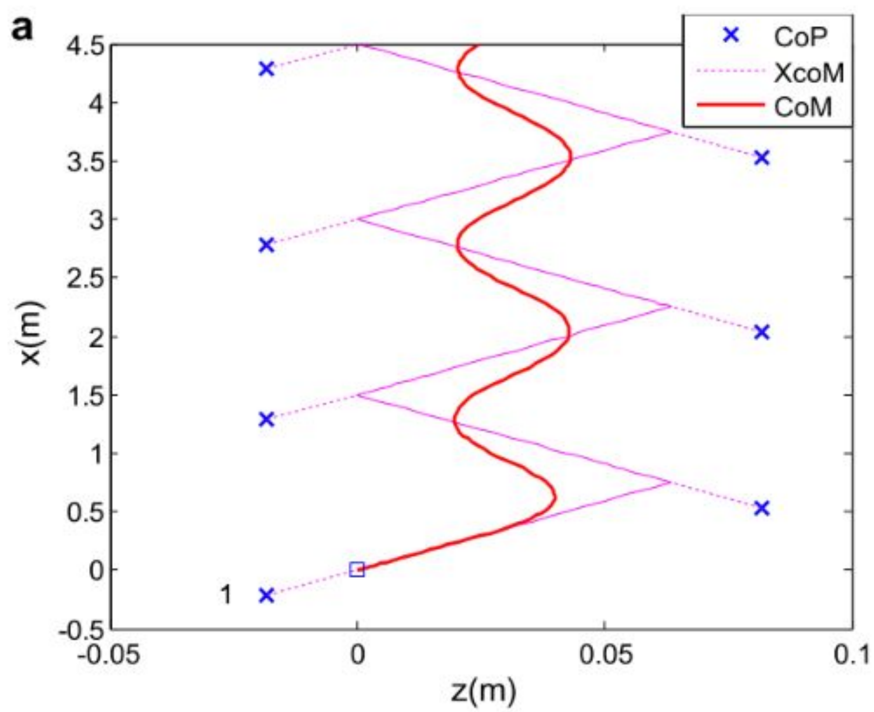
Professor: Auke Ijspeert
Presented by: Milad Shafiee

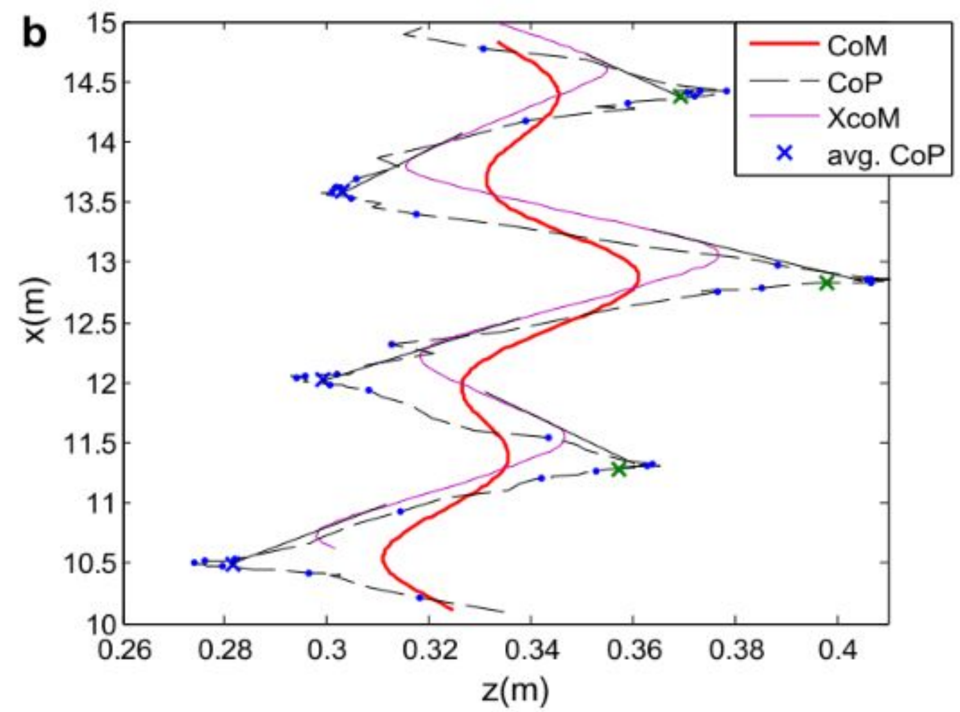
Asimo runs at 9 Km/h by using the DCM concept for locomotion planning!



Takenaka, Toru, Takashi Matsumoto, and Takahide Yoshiike. "Real time motion generation and control for biped robot-1 st report: Walking gait pattern generation." 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE, 2009.(Citation:299)

Human locomotion data is well-fitted with the Extrapolated Center of Mass(XCoM) Concept



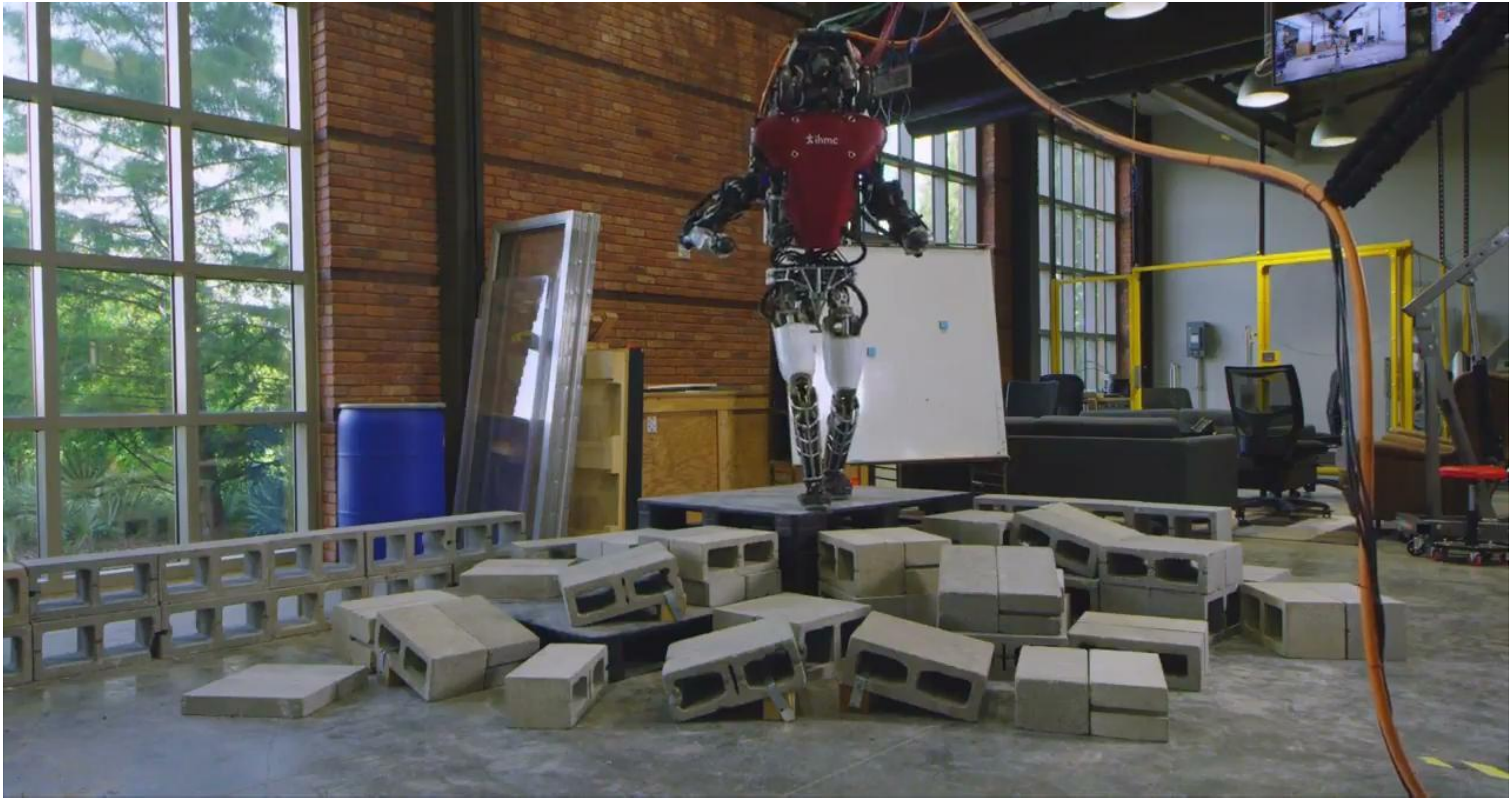


- XCoM(DCM) based motion planning
- Human experimental data of locomotion

Hof, At L. "The 'extrapolated center of mass' concept suggests a simple control of balance in walking." Human movement science 27.1 (2008): 112-125.(Citation:456)

Hof, A. L., M. G. J. Gazendam, and W. E. Sinke. "The condition for dynamic stability." Journal of biomechanics 38.1 (2005): 1-8.(Citation:1258)

IHMC came in 2nd place in Darpa Robotics Challenge(DRC) by having the DCM planner that you will implement in the project!



Englsberger, Johannes, Christian Ott, and Alin Albu-Schäffer. "Three-dimensional bipedal walking control based on divergent component of motion." Ieee transactions on robotics 31.2 (2015): 355-368.(254)

Koolen, Twan, et al. "Design of a momentum-based control framework and application to the humanoid robot atlas." International Journal of Humanoid Robotics 13.01 (2016): 1650007.(160)

Linear Inverted Pendulum (LIP) model (2D

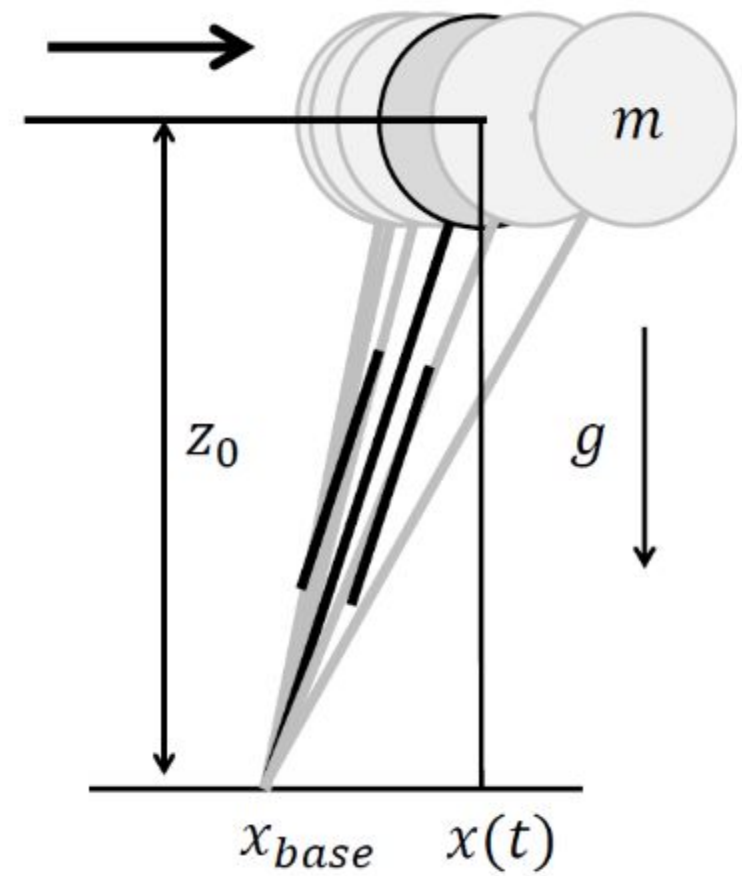
- Solving the equation of motion:

$$\ddot{x}(t) = \frac{g}{z_0}(x(t) - x_{base}),\ \omega = \sqrt{g/z_0}$$

$$x(t) = Ae^{-\omega t} + \boxed{Be^{\omega t}} + x_{base}$$

$$A = (-\dot{x}(0)/\omega + x(0) - x_{base})/2$$

$$B = \boxed{(\boxed{\dot{x}(0)/\omega + x(0)} - x_{base})/2}$$

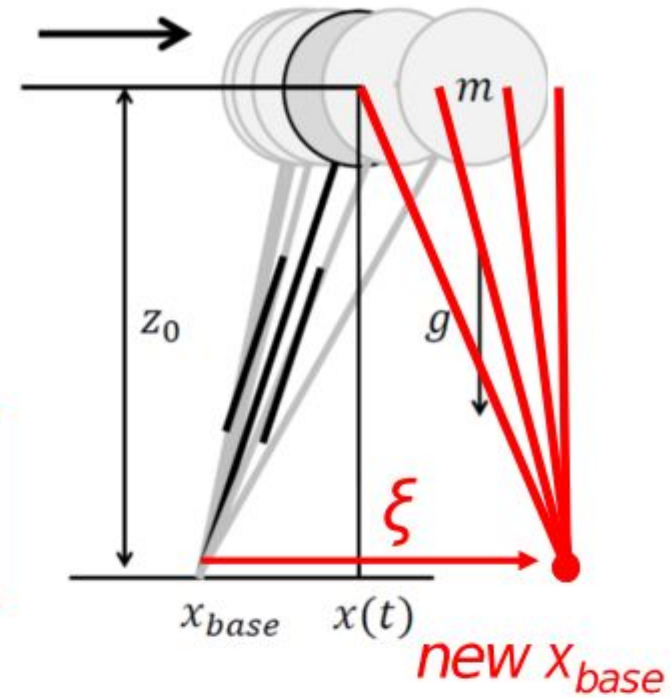


- We thus have a closed form (i.e. analytical solution) that allows us to predict the forward movement of the center of mass

Divergent component of motion (DCM)

- It is therefore important to monitor the DCM, and to plan the foot steps (i.e. x_{base}) to bring the robot (the CoM) where you want and to prevent falling.

$$\boxed{\xi = x + \frac{\dot{x}}{\omega}}$$



- The DCM corresponds to the ***instantaneous capture point.***
- Indeed by setting the next foot step (i.e. x_{base}) to ξ at the beginning of a step, the time evolution of x goes to zero (i.e. the pendulum stops).

$$\dot{\xi} = \omega(\xi - x_{base})$$

$$\dot{x} = -\omega(x - \xi)$$

- Takenaka, Toru, Takashi Matsumoto, and Takahide Yoshiike. 2009. "Real Time Motion Generation and Control for Biped Robot: 1st Report: Walking Gait Pattern Generation." In *Proceedings of* IROS 2009.
- Englsberger et al (2014). Trajectory generation for continuous leg forces during double support and heel-to-toe shift based on divergent component of motion. In *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems* (pp. 4022-4029). IEEE.

This will be tested in the mini project with the Atlas simulation!

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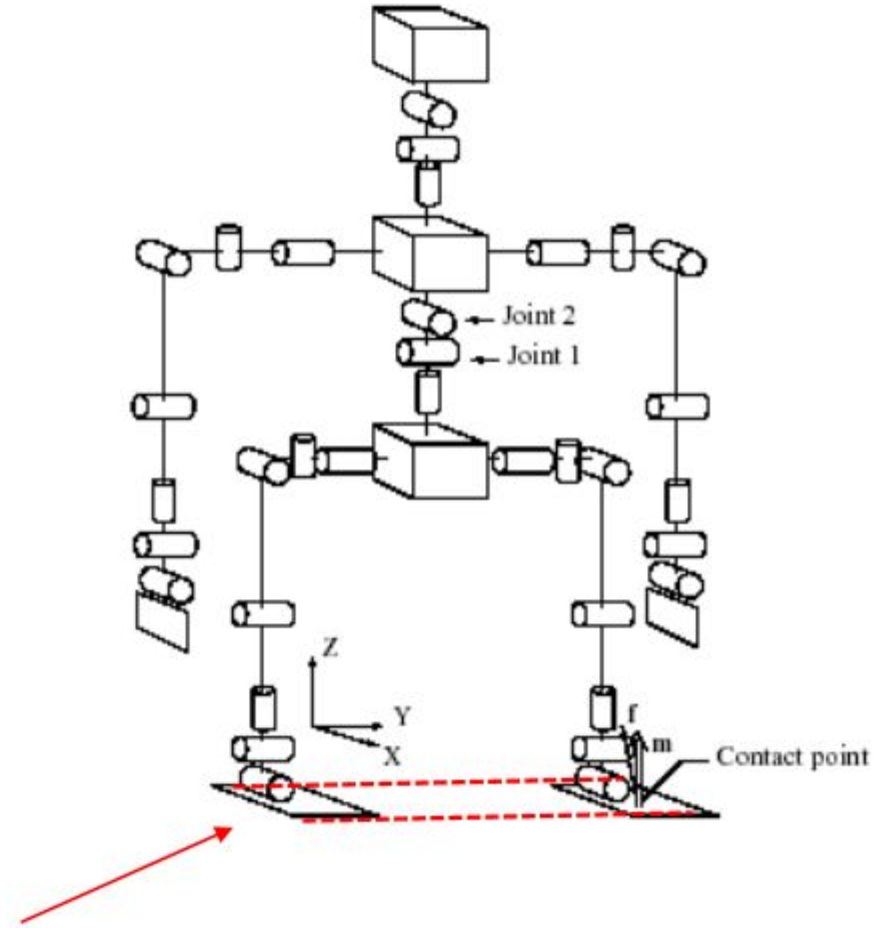
Examples of model-based approaches

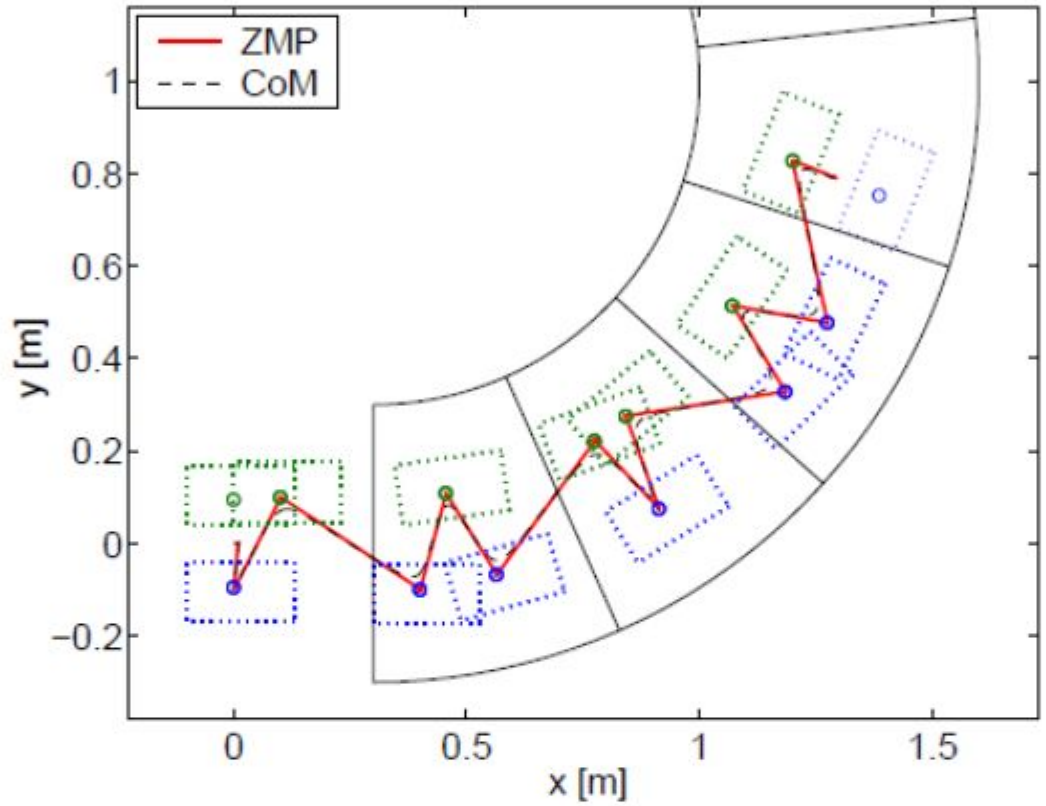
Model-based control:

1. **trajectory based methods (ZMP)**
2. Virtual leg control (Raibert)
3. Virtual model control (Pratt et al)
4. Hybrid Zero Dynamics control
5. Planning methods (Little dog project)
6. Inverse dynamics and optimization

ZMP



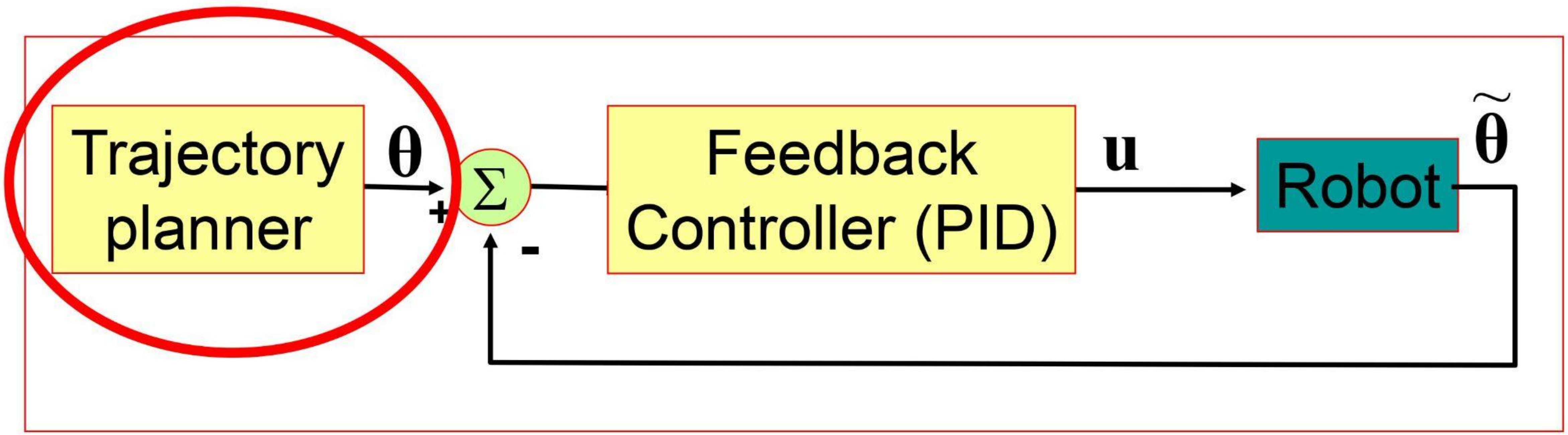
Foot-print polygon



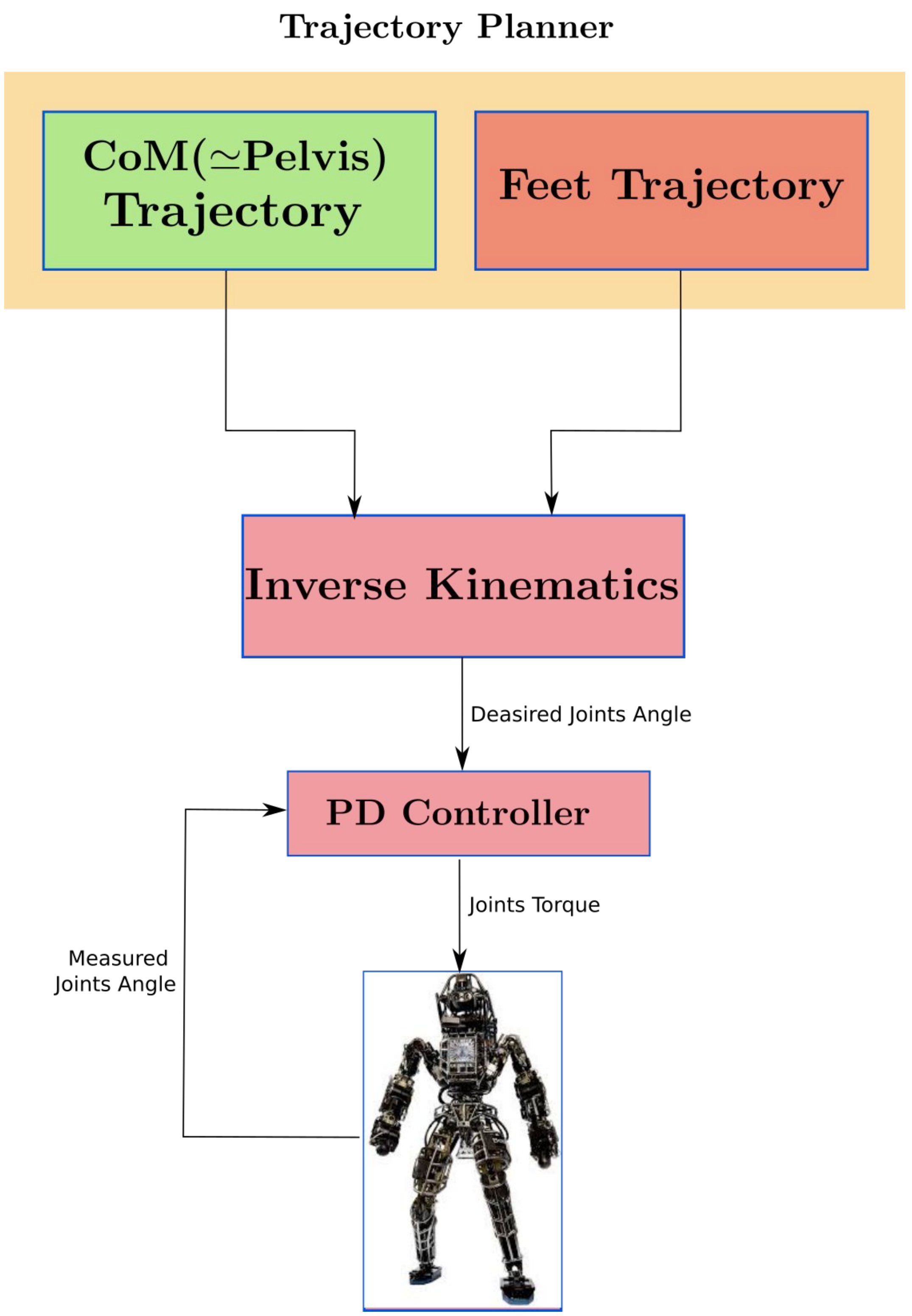
Kajita, et al. 2003. "Biped Walking Pattern Generation by Using Preview Control of Zero-Moment Point." In *ICRA 2003* https://doi.org/10.1109/ROBOT.2003.1241826.

Locomotion is stable if the ZMP remains within the foot-print polygons over time

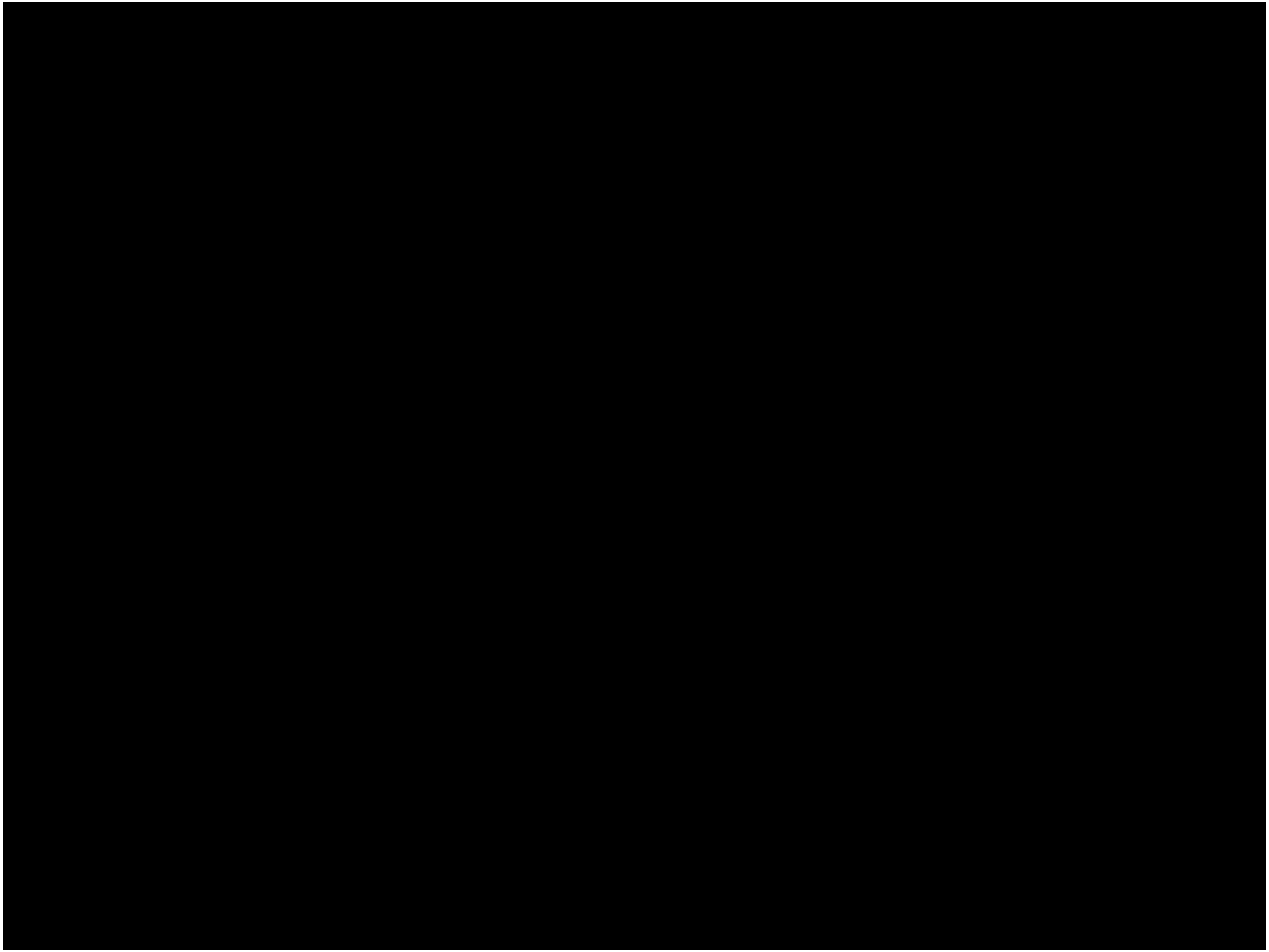
Minimalistic control diagram



θ	Desired robot posture
$\tilde{\theta}$	Actual robot posture
$\mathbf{u}$	Command (torque)

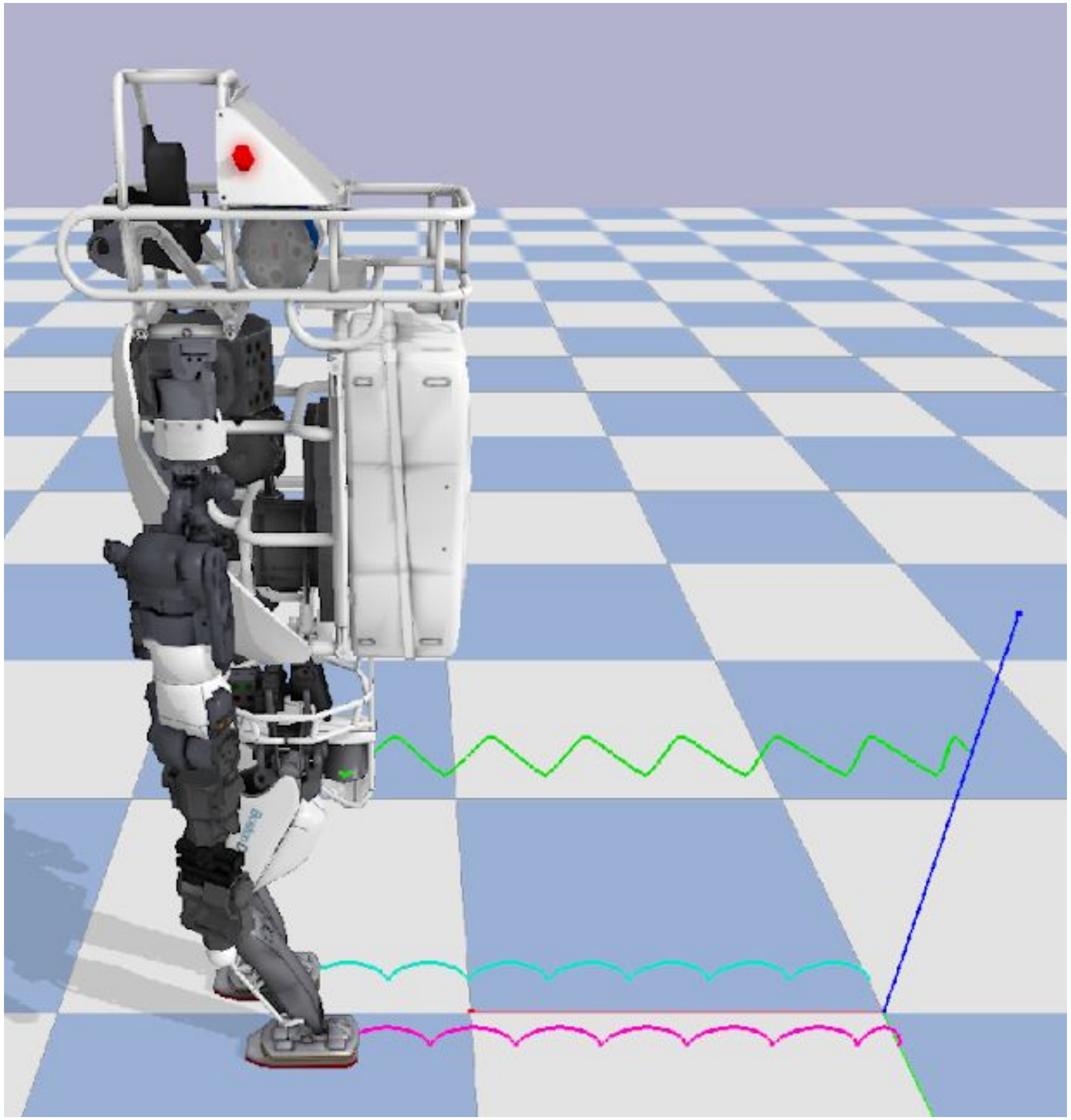

Trajectory Planner
CoM(≃Pelvis) Trajectory
Feet Trajectory
Inverse Kinematics
Deasired Joints Angle
PD Controller
Joints Torque
Measured Joints Angle

Project Definition: Atlas Walking with DCM Planner in Pybullet



Englsberger, Johannes, Christian Ott, and Alin Albu-Schäffer. "Three-dimensional bipedal walking control based on divergent component of motion." Ieee transactions on robotics 31.2 (2015): 355-368.(254)

Mini-Project: Atlas Walking with DCM Planner in Pybullet



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Linear Inverted Pendulum Model(LIPM)-Divergent Component of Motion(DCM)

$$\ddot{x}_c = \omega^2(x_c - CoP)$$

x_c Center of mass position

CoP Center of Pressure

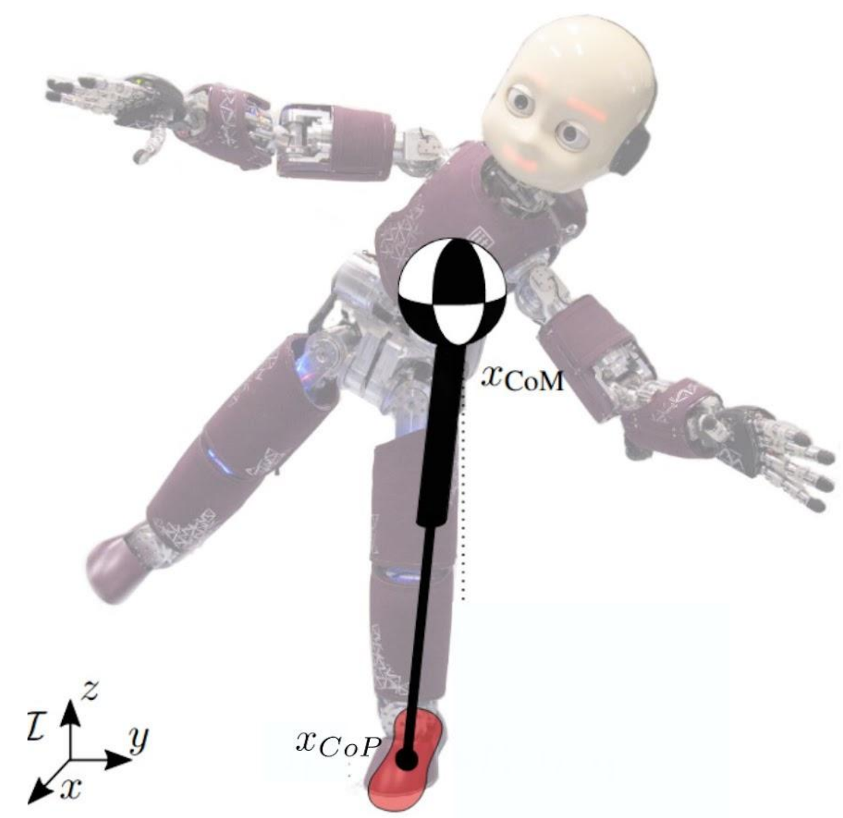
g Gravity Acceleration

z Center of mass height(constant)

$$\omega = \sqrt{\frac{g}{z}}$$

$$\xi_x = x_c + \frac{\dot{x}_c}{\omega}$$

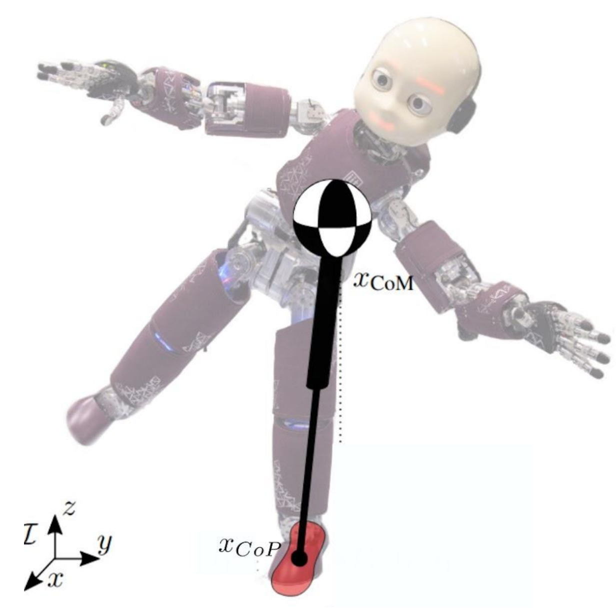
ξ DCM



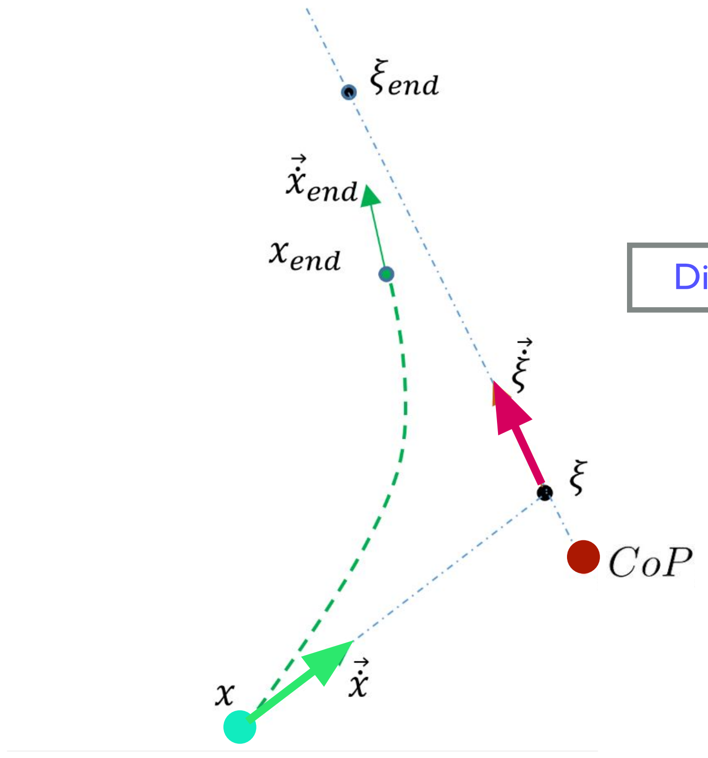
Pratt, Jerry, et al. "Capture point: A step toward humanoid push recovery." 2006 6th IEEE-RAS international conference on humanoid robots. IEEE, 2006.(Citation:1013)

DCM Dynamics

$$\ddot{x}_c = \omega^2(x_c - CoP)$$



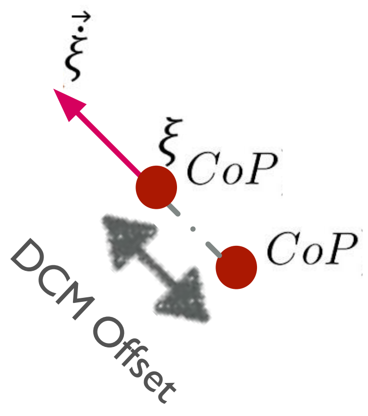
$$\xi_x = x_c + \frac{\dot{x}_c}{\omega}$$



$$\dot{\xi} = \omega(\xi - CoP) \qquad \dot{x} = -\omega(x - \xi)$$

Divergent Component of Motion(DCM) | Convergent Component of Motion

Why is capture point another name for DCM?



Koolen, Twan, et al. "Capturability-based analysis and control of legged locomotion, Part 1: Theory and application to three simple gait models." The international journal of robotics research 31.9 (2012): 1094-1113.(Citation:433)

Solution of DCM ode

$$\dot{\xi} = \omega(\xi - CoP)$$

We can solve this ode by considering that CoP is a constant value (During single support phase)

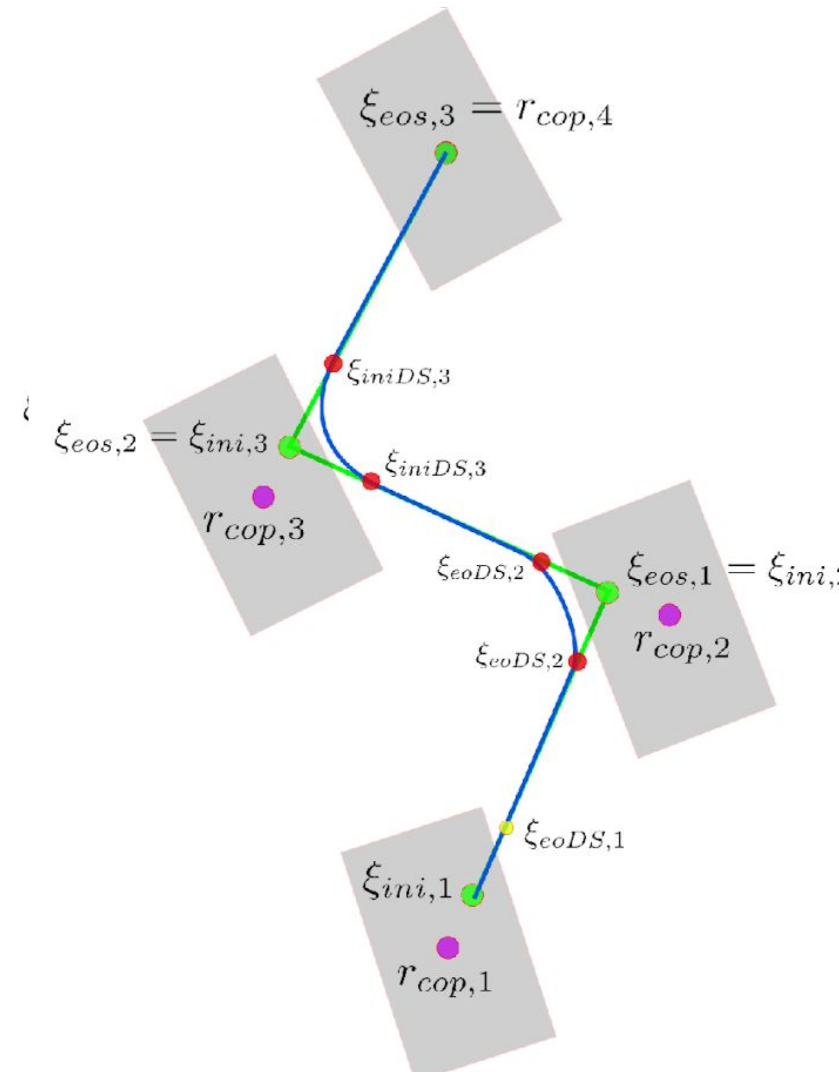
$$\xi(t) = CoP + e^{\omega t}(\xi_0 - CoP)$$

Pratt, Jerry, et al. "Capture point: A step toward humanoid push recovery." 2006 6th IEEE-RAS international conference on humanoid robots. IEEE, 2006.(1013)

DCM Motion Planning

$$\xi(t) = CoP + e^{\omega t}(\boxed{\xi_0} - CoP)$$

- Plan foot step position and step duration(T)
- Place the desired CoP in a location inside of the foot print
- Place the last DCM position on the last CoP(Capturability constraint)
- Find the initial DCM position for each step recursively based on DCM equation
- By having initial DCM and DCM equation we can find DCM Trajectory for SS
- Select the desired double support(DS) phase duration
- Based on the desired DS duration find DCM boundary conditions for DS
- Use a cubic interpolation for finding DCM trajectory in DS phase
- Replace the DCM planned trajectory for the DS with the corresponding part that was for single support



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DCM Motion Planning for Single Support(SS)

$$\xi(t) = CoP + e^{\omega t}(\xi_0 - CoP)$$

- Place the last DCM position on the last CoP(Capturability constraint)

$$\xi_{eos,i} = r_{cop,i} + (\xi_{ini,i} - r_{cop,i})e^{\omega T}$$

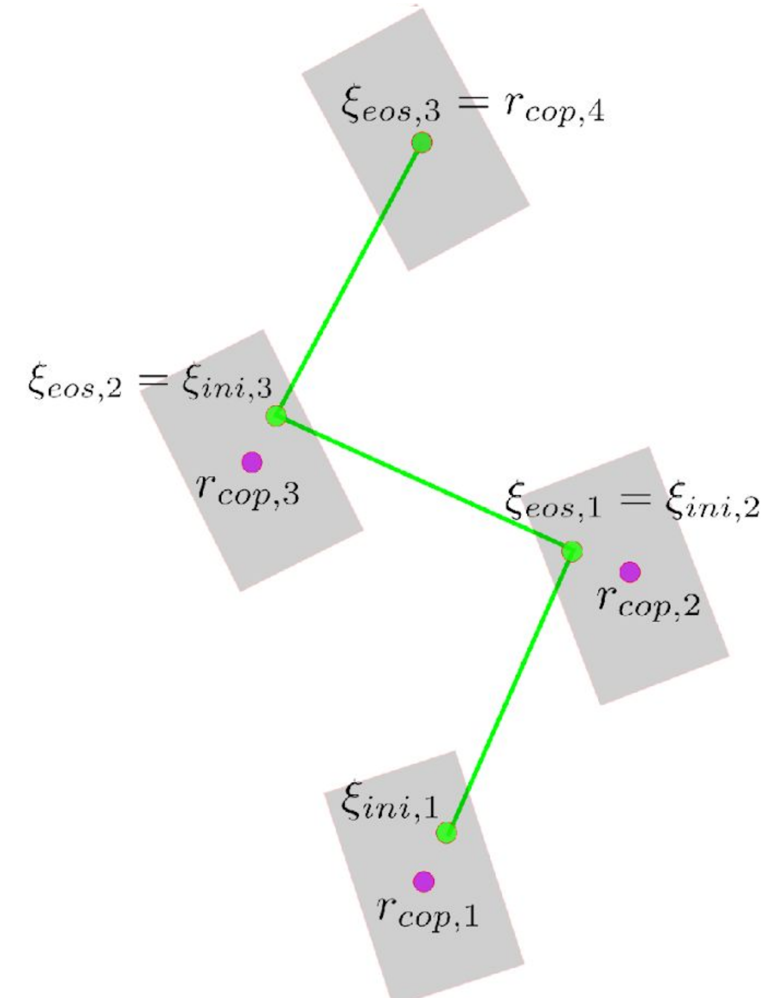
$$\xi_{ini,i} = r_{cop,i} + (\xi_{eos,i} - r_{cop,i})e^{-\omega T}$$

- Find the initial DCM position for each step recursively based on DCM equation

$$\xi_{eos,i-1} = \xi_{ini,i}$$

- By having initial DCM and DCM equation we can find DCM Trajectory for SS:

$$\xi_i(t) = r_{cop,i} + (\xi_{eos,i} - r_{cop,i})e^{\omega(t-T)}$$



The "internal" timestep ***t*** is reset at the beginning of each step, i.e., $\boldsymbol{t} \in$ **[0,T]** (T is the duration of the step).

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DCM Motion Planning for Double Support(DS)

- Select the desired double support(DS) phase duration

$$\Delta t_{DS,ini} = \alpha_{DS,ini} t_{DS}$$

$$\Delta t_{DS,end} = (1 - \alpha_{DS,ini}) t_{DS}$$

- Based on the desired DS duration find DCM boundary conditions for DS

$$\xi_{eoDS,i} = r_{cop,i} + (\xi_{ini,i} - r_{cop,i}) e^{\omega \Delta t_{DS,end}}$$

$$\xi_{iniDS,i} = r_{cop,i-1} + (\xi_{ini,i} - r_{cop,i-1}) e^{-\omega \Delta t_{DS,ini}}$$

- Use a cubic interpolation for finding DCM trajectory in DS phase

$$\begin{bmatrix} \frac{2}{T_{DS}^3} & \frac{1}{T_{DS}^2} & -\frac{2}{T_{DS}^3} & \frac{1}{T_{DS}^2} \\ -\frac{3}{T_{DS}^2} & -\frac{2}{T_{DS}} & \frac{3}{T_{DS}^2} & -\frac{1}{T_{DS}} \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \xi_{iniDS,i} \\ \dot{\xi}_{iniDS,i} \\ \xi_{eosDS,i} \\ \dot{\xi}_{eosDS,i} \end{bmatrix} = P$$

$$\begin{bmatrix} \xi(t) \\ \dot{\xi}(t) \end{bmatrix} = \begin{bmatrix} t^3 & t^2 & t & 1 \\ 3t^2 & 2t & 1 & 0 \end{bmatrix} P$$

- Replace the DCM planned trajectory for the DS