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Passive Dynamic Walkers

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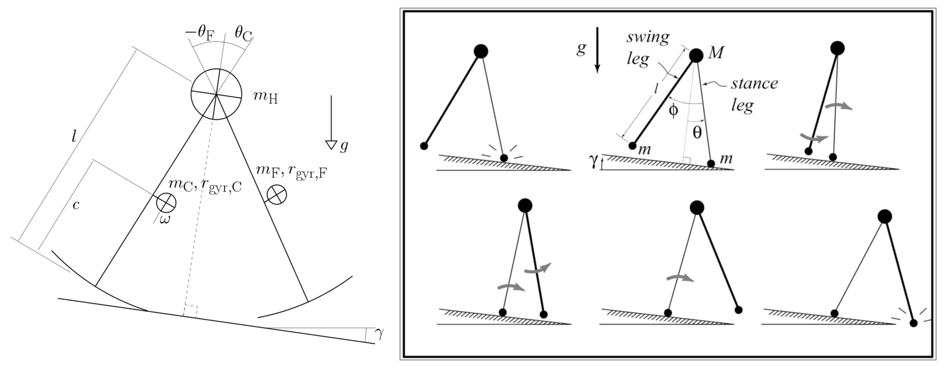
Principle

Passive dynamic walkers are based on the idea of being mainly actuated through gravity and inertia. Like the **natural dynamics** of a wheel rolling down a slope, the mechanical structure alone exhibits stable locomotion without additional external energy.

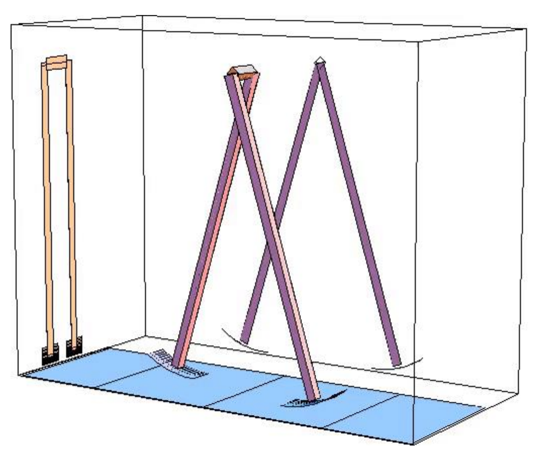


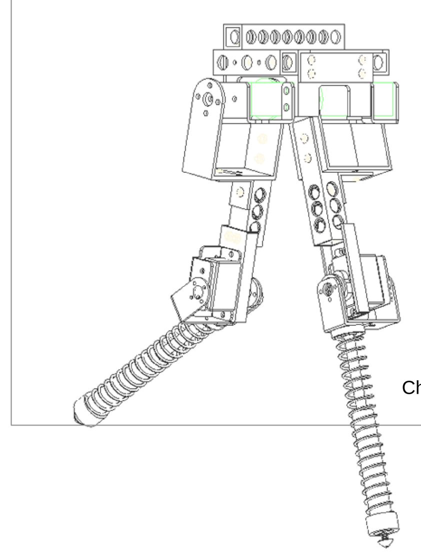
If one splits the outer rim of a wheel halfway between each stroke, discards all but two and presumes that the hip has a large mass, one achieves the simplest model for walking; the **synthetic wheel**. While the stance leg (C) rolls at a constant speed, the free leg (F) swings sinusoidal as pendulum:

$$\theta_{\mathrm{C}}(\tau_0) = \alpha_0 = -\alpha_0 + \Omega_{\mathrm{C}}\tau_0$$

$$\theta_{\mathrm{F}}(\tau_0) = -\alpha_0 = \alpha_0 \cos(\omega_{\mathrm{F}}\tau_0) + \frac{\Omega_{\mathrm{C}}}{\omega_{\mathrm{F}}}\sin(\omega_{\mathrm{F}}\tau_0)$$

Instead of using semi-circular feet one can also model point feet in the **compass gait** model, and model the stance as an **inverted pendulum**. By analyzing the deviation in state space of step-to-step trajectory, periodic solutions can be found, which are robust to limited perturbations. Passive dynamic walkers are often only dynamically stable, but not statically.





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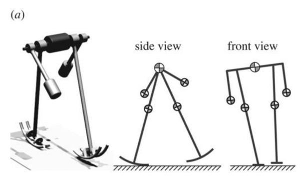
Design

In the design of PDWs, the robot's locomotion and control through the gait are paramount to its ability to function and take priority over other design considerations, as there are no active components to re-balance the system.



Most physical walkers are characterized by simple designs that only include the essential degrees of freedom for walking; **legs** rotating around a heavy **hip** mass. The legs are long and stiff, in order to have high potential energy during the swinging motion, and preservation of angular momentum during stance. The parameters for a stable gait can be found analytically, but they often show a narrow working parameter space.

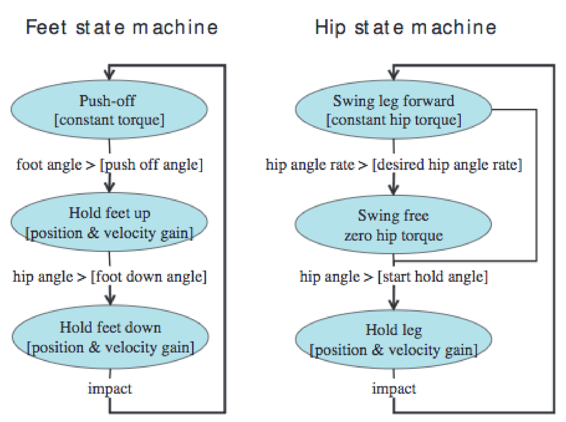
Knees as a double linked pendulum during leg-swing can solve the foot scuffing problem. Adding additional features like a trunk and arms provide **lateral stabilization**. Here the arms are mechanically coupled with the opposite legs, such that arms and legs are swinging inverted to each other.

Control

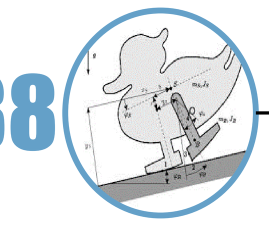
The motion space for passive dynamic walking is restricted to certain environmental conditions such as a declining slope and gravitational acceleration.

In order to enable the concept of passive dynamic walking on a leveled plane, **actuators and simple control mechanisms** can be introduced. This system enhancement ensures both additional stability as well as a compensation for the energy loss. In this way we **enlarge the stable parameter space** which results in a more robust system.

Taking the Cornell Ranger as an example for controlled passive dynamic walking, simple counter acting and steering can be explained. In order to enable a stable walking and steering, the robot's **hip and feet are actuated.** The graph below shows the states and conditions for controlling the hip and feet actuators.
Besides a walk and torque controller the Cornell Ranger consists of a state estimator, that gets angles and angle velocities as sensory input in order to calculate the robots state.



Timeline



~1888

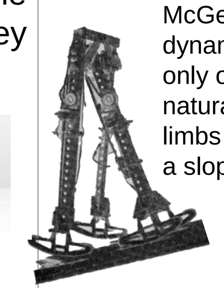
EARLY DEVELOPMENTS

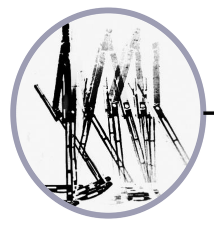
Toys that could mechanically walk down a inclined slope with no motors.

1989

DR. TAD MCGEER

Introduce the term Passive Dynamic Walkers McGeer's early passive-dynamic machines relied only on gravity and the natural swinging of their limbs to move forward down a slope. [1]

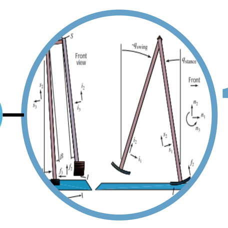




1990

PASSIVE WALKING WITH KNEES

Knees solve the problem of feet colliding with the ground (scuffing) when the leg swings forward [2]



1999

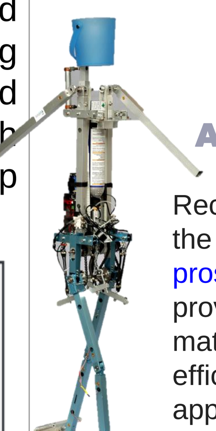
STABILIZATION OF LATERAL MOTION IN PASSIVE DYNAMIC WALKING

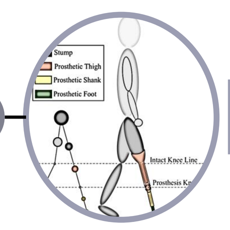
Advances and research in anti-scuffing techniques (A. Ruina) [6] and mass center stabilization (Art Kuo) [3]

2003

DYNAMIC ARM SWINGING

Design improvements and implementation of swinging arms to expand the inverted pendulum and pendulum system and thus develop more stable robots.





Now

APPLICATIONS

Recently there is a role in the design and control of prosthetics. Since PDW provides the mathematical models of efficient motion, it is an appropriate avenue to develop efficient for amputees. Andrew Hansen, Steven Gard and others have done extensive research in developing better footing.

Robot examples

Museon Walker (2001)

A fully passive walking robot that is used to demonstrate the basic principle behind passive dynamic walking.

Requires a sloped walking surface

TU Delft

- Height: 0.8 m
- Weight: ~ 3.5 kg
- DoFs: 2

Juan Martinez-Moritz

Denise (2004) [4]

Introducing knees and an upper body stability with on-board power, McKibben muscles and controllable foot latch.

TU Delft

- Height: 1.3 m
- Weight: ~ 15 kg
- DoFs: 5
- CoT: ≥ 0.03

Gyri Reiersen

Toddler (2005) [5]

Learns to walk on flat surfaces in under 20 minutes through reinforcement.

MIT

- Height: 0.44 m
- Weight: ~2.9 kg
- DoFs: 4/5
- CoT: ≥ 0.02

Robin Petereit

Cornell Ranger (2006) [6]

Efficiency and reliability of walking 65.2 km was achieved by event-based control and a numerically optimized trajectory.

Cornell University

- Height: 1m
- Weight: 9.9 kg
- DoFs: 6
- CoT: ~ 0.19

Florian Lay

BlueBiped (2008) [7]

The legs are completely passive. The momentum of each step is enough to throw it into another step.

Nagoya Inst. of Tech.

- Height: 1 m
- Weight: ~ 10 kg
- DoFs: 4
- Walked 13 h, and 15 km

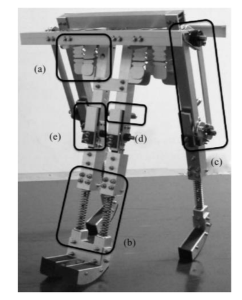
Natalia Paredes

PDR400 (2010)

Elastics are used for passive control with animal inspired hyperextension of the knee.

Tohoku University

- Height: 0.40 m
- Weight: 4.8 kg
- Speed: 0.83 m/s

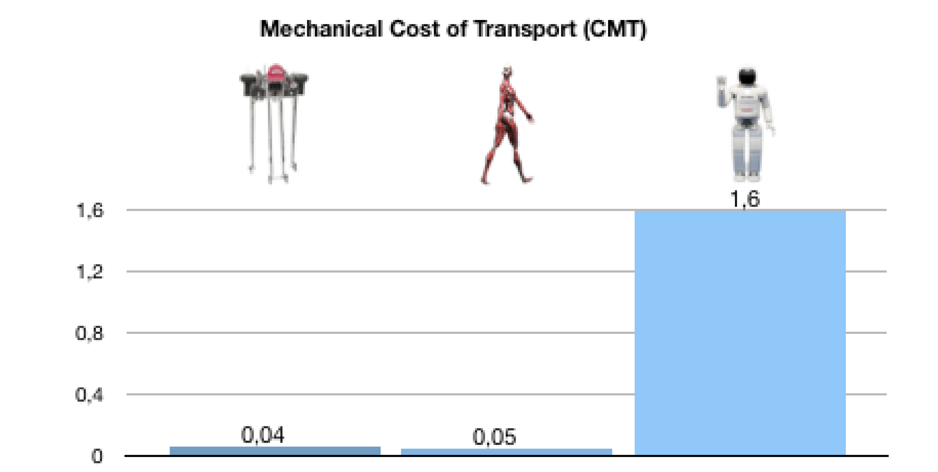


Jose Mirzai

Efficiency

One of the most significant motivations for researching PDWs is their energy efficiency when adding actuators. A common measure is the dimensionless **cost of transportation** (CoT); the amount of energy to carry a unit weight a unit distance. We distinguish between specific energetic cost of transport (CET) and specific mechanical cost of transport (CMT). Whereas CET considers the total energy consumed by the system, the CMT only considers the **positive mechanical work by the actuators**.

The following chart compares the minimum CMT between a human, the PDW Cornell Ranger and Honda's biped ASIMO. It shows that PDWs can reach human-like cost of transport, whereas robots with higher degrees of freedom, like ASIMO, require as much as 40 times more.



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