Chair of Applied Mechanics
TUM School of Engineering and Design
Technical University of Munich

Comparison of Controllers for Trunk Stabilization in a Bipedal Robot

Initial Presentation, Master's Thesis

Felix Schausberger

October 11, 2022

Supervisor: *Dr.-Ing. Daniel Renjewski*
Examiner: *Prof. dr.ir. Daniel J. Rixen*

Notes of Slide 1:

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Problem description

Balancing the trunk on long legs is a major challenge in bipedal walking.
Task Description:

1. Quantify and analyze different trunk pitch control strategies.
2. Implement relevant controllers in JenaFox simulation.
3. Evaluate selected approaches on robotic test environment.

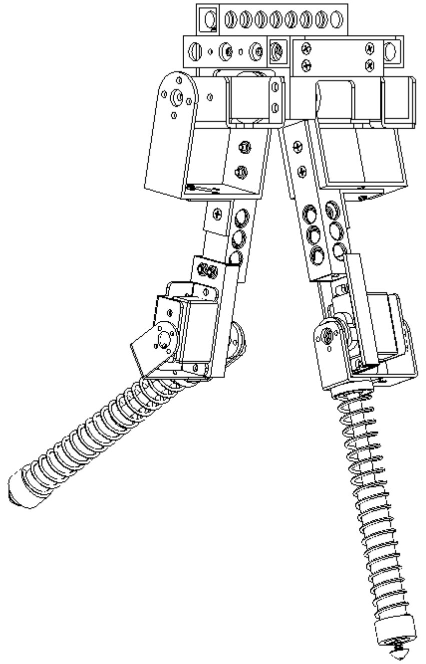
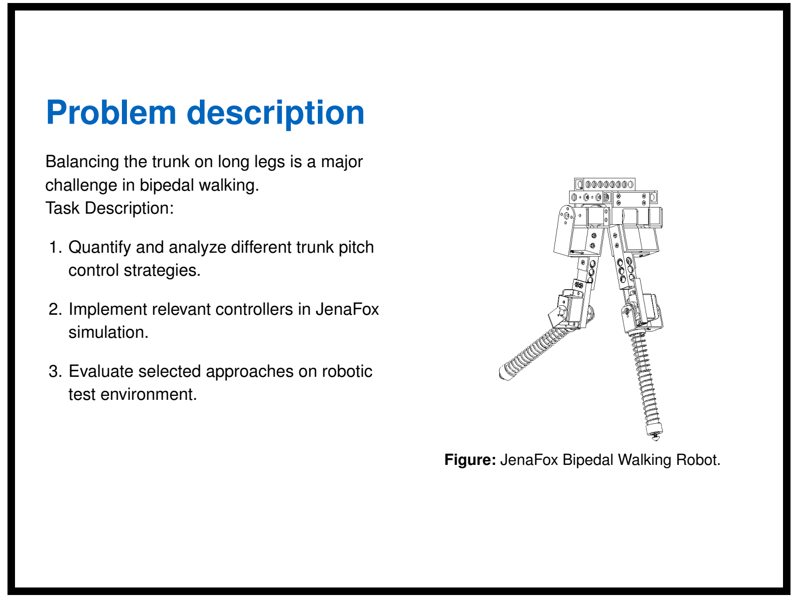


Figure: JenaFox Bipedal Walking Robot.

Notes of Slide 2: Problem description

- Bipedal walking: Complex task, highly dynamical gait that involves flight phase, during which no force can be applied to environment
- Among others, one of the biggest challenges: balance torso on long legs
- Analyze, implement, evaluate (JenaFox on left)



Objective of the Thesis

1. Starting point:
   Stiff spring limits rotation of trunk

2. Approach:
   Gradually reduce spring while adjusting controller

   - **Collision based** [Lee+11]
   - H-SLIP [SS12]
   - Virtual Pivot Point (VPP) [MRS08] [Mau+10]

3. Objective:
   Free rotation without restrictions

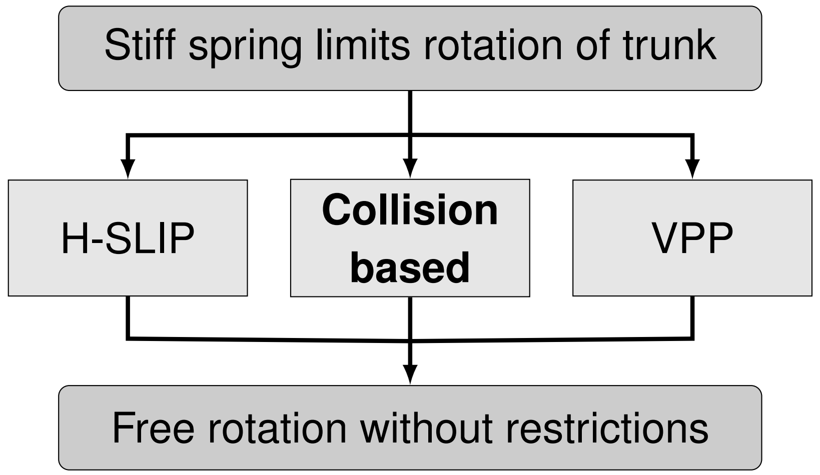
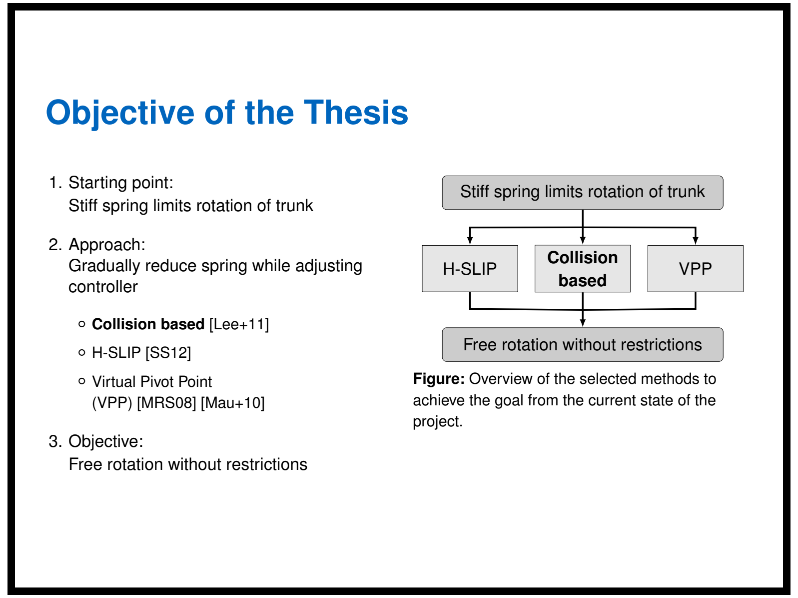


Figure: Overview of the selected methods to achieve the goal from the current state of the project.

Notes of Slide 3: Objective of the Thesis

- David Lee and others, premise: Discrete footfalls prevent consistent orthogonal relationship between force and velocity vectors, thus kinetic energy is lost as GRF performs mechanical work at CoM
- Extension of canonical SLIP with constant hip torque and linear leg damping during stance called Hip Actuated Spring Loaded Inverted Pendulum (H-SLIP)
- VPP, a fixed point on the torso above the CoM, where GRF are directed to via hip torque
- Overall objective: Get rid of spring and enable a free rotation of the trunk without restrictions
- Note: Friction still included, just not as spring


Objective of the Thesis
1. Starting point:
Stiff spring limits rotation of trunk
2. Approach:
Gradually reduce spring while adjusting controller
Collision based [Lee+11]
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Virtual Pivot Point (VPP) [MRS08] [Mau+10]
3. Objective:
Free rotation without restrictions
Stiff spring limits rotation of trunk
H-SLIP
Collision based
VPP
Free rotation without restrictions
Figure: Overview of the selected methods to achieve the goal from the current state of the project.

Comparison criteria

- Maximum allowable perturbation [RS08] [Mau+10]
  - Limit cycle: $\upsilon_{n+1} = \upsilon_n$
  - Poincaré map: $\upsilon_{n+1} = S(\upsilon)$
- Disturbance response
- Mechanical cost analysis

Possible disturbances:

- Horizontal velocity $\dot{x}_0$
- Floor height $\dot{y}_0$
- Torso angular rate $\dot{\phi}_0$

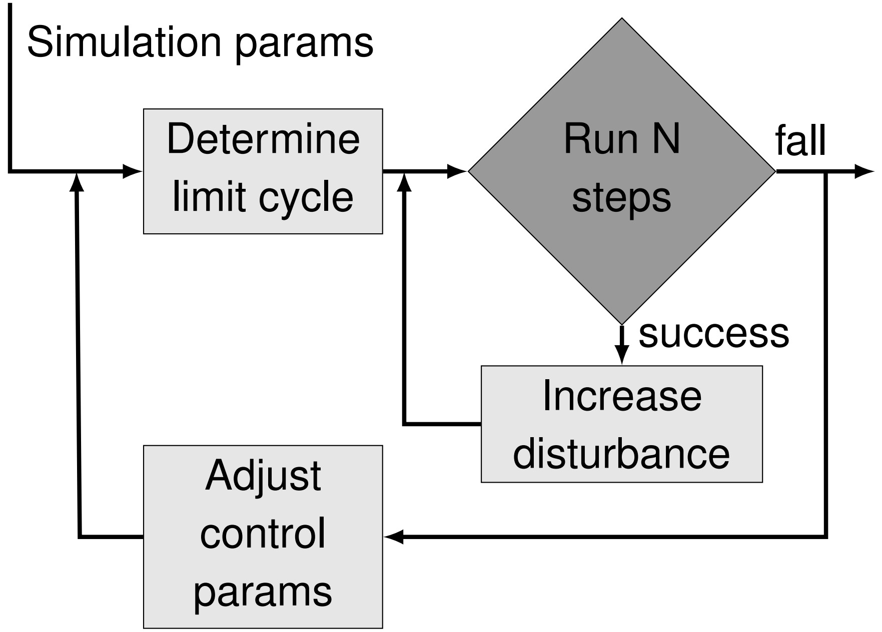
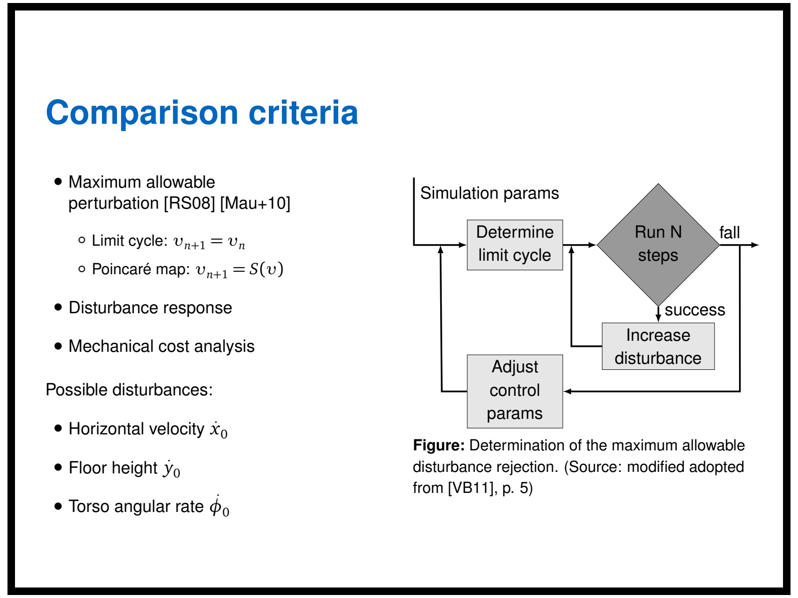


Figure: Determination of the maximum allowable disturbance rejection. (Source: modified adopted from [VB11], p. 5)

Notes of Slide 4: Comparison criteria

- Disturbance rejection: maximum allowable perturbation of model
- First, limit cycle, which model is in when initial states remain unchanged for consecutive strides, will get determined
- Important role: Poincaré (Púokaré) map: Mapping between initial states of consecutive strides
- Explain model
- Other possible comparison criteria: Disturbance response: Recovery process of model after disturbance, mechanical cost analysis
- Possible disturbances: x_0, y_0, ϕ_0: Introduced as single error on initial state of limit cycle



Work Plan and necessary Resources

Tools:

- Controller implementation and simulation in MATLAB® and Simulink® (2022a)
  - Version Control System (git via gitlab)
- Documentation and scientific discussion in Visual Studio Code with LaTeX
  - Version Control System (git via codeberg)
  - Citation and reference management with JabRef

Notes of Slide 5: Work Plan and necessary Resources

Work Plan and necessary Resources
Tools:
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Time schedule

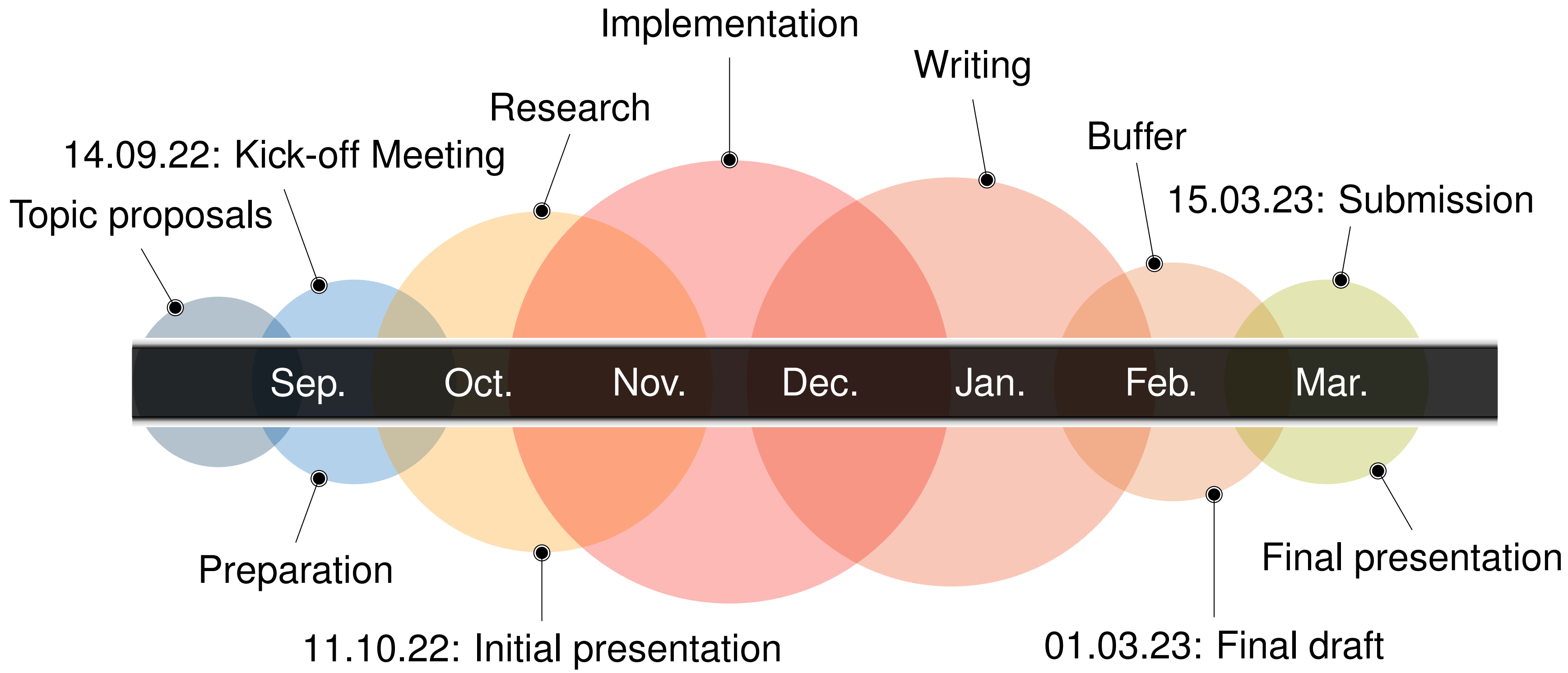
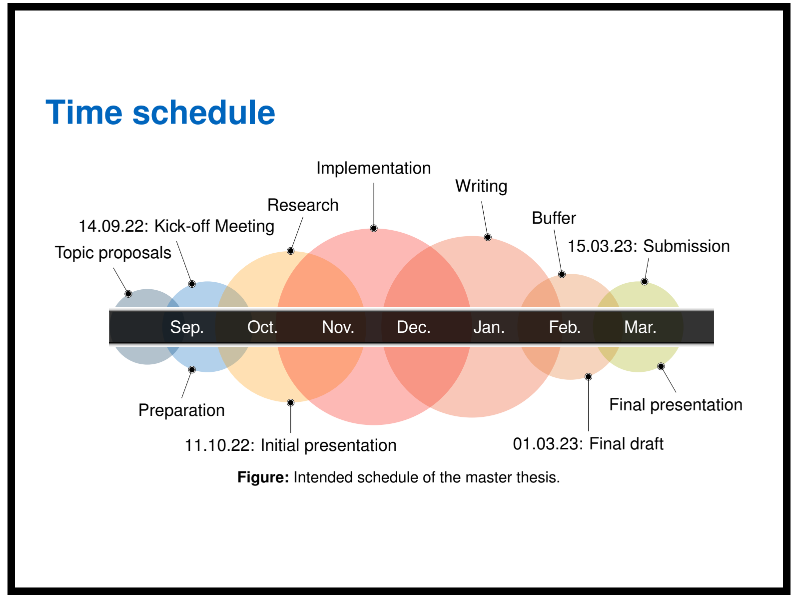


Figure: Intended schedule of the master thesis.

Notes of Slide 6: Time schedule



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Summary

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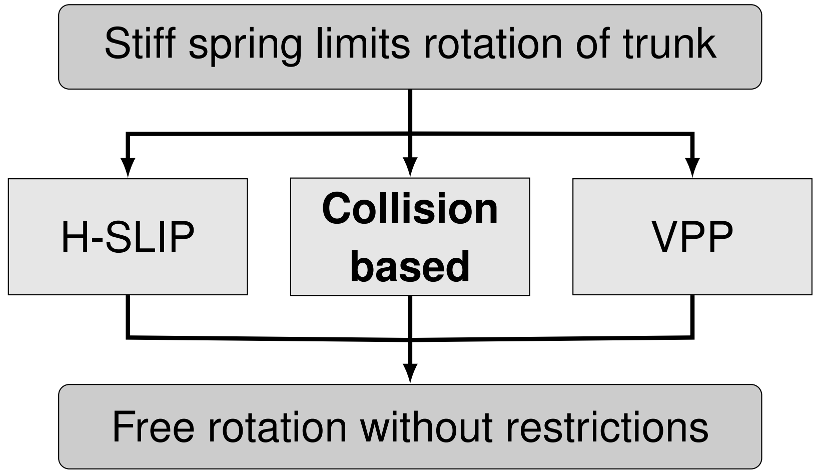
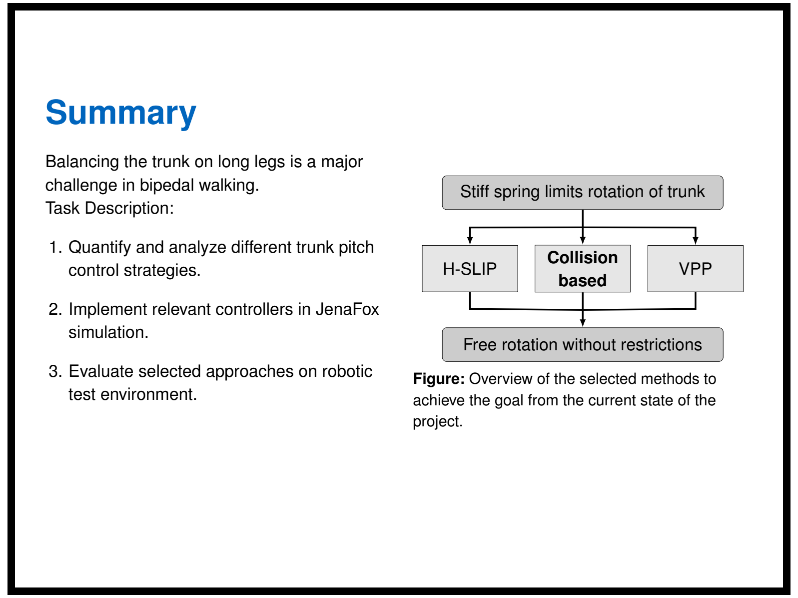


Figure: Overview of the selected methods to achieve the goal from the current state of the project.

Notes of Slide 7: Summary



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Collision based approach

- If $F \perp V$: No collision occurs
- Discrete footfalls: $F \not\perp V$: Kinetic energy is lost [AB18]

Key advantages: [Lee+13]

- Center of Mass (CoM) dynamics get considered in every instance of contact during stride
- Dimensionless
- Independent of a priori models
- Explains the mechanical Cost of Transport (CoT) from first principles

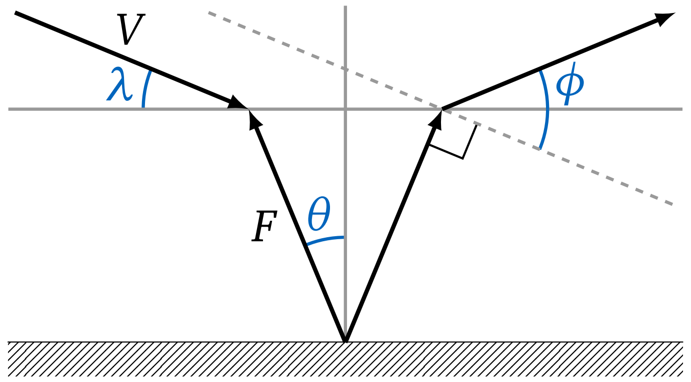
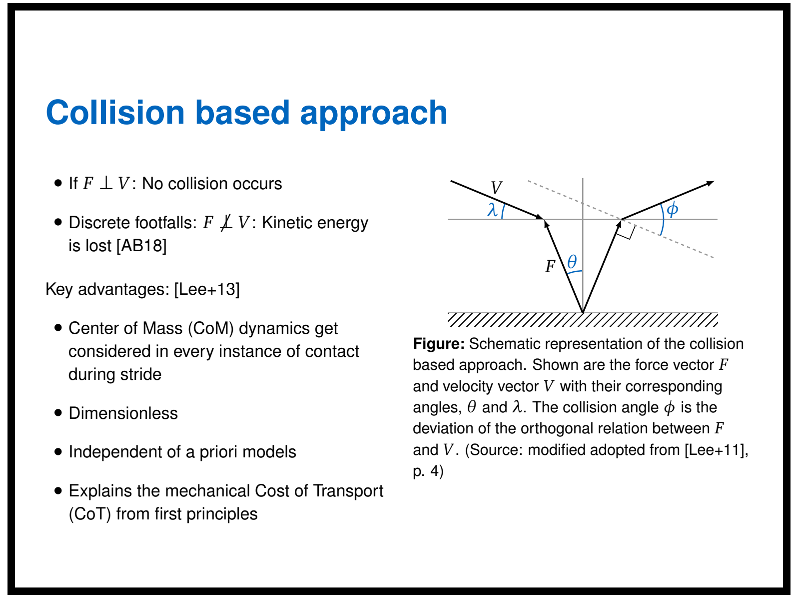


Figure: Schematic representation of the collision based approach. Shown are the force vector F and velocity vector V with their corresponding angles, θ and λ. The collision angle ϕ is the deviation of the orthogonal relation between F and V. (Source: modified adopted from [Lee+11], p. 4)

Notes of Slide 9: Collision based approach

- Mechanics: Modeled in terms of “inelastic” collisions by limb with ground
- If $F \perp V$: No collision occurs: No work done at CoM, e.g. wheel without rim but infinite spokes
- Intermittent foot contacts during legged locomotion result in relatively abrupt, collision-like changes in CoM direction, which require mechanical work
- Dimensionless, allowing comparisons across species of vastly different size and comparisons across gravity conditions
- Independent of a priori models of CoM mechanics: applies equally to any gait

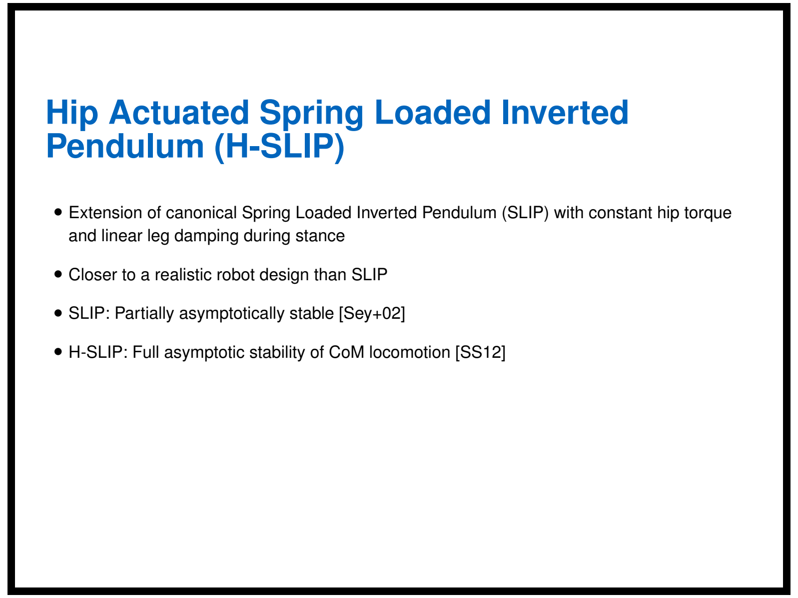


Hip Actuated Spring Loaded Inverted Pendulum (H-SLIP)

- Extension of canonical Spring Loaded Inverted Pendulum (SLIP) with constant hip torque and linear leg damping during stance
- Closer to a realistic robot design than SLIP
- SLIP: Partially asymptotically stable [Sey+02]
- H-SLIP: Full asymptotic stability of CoM locomotion [SS12]

Notes of Slide 10: Hip Actuated Spring Loaded Inverted Pendulum (H-SLIP)

- SLIP: energy conserving: Although it can return to periodic locomotion when subjected to perturbation in velocity direction, it cannot stabilize system energy



Virtual Pivot Point (VPP)

- Takes leg orientation into account
- If the VPP is aligned with the leg, no torso torque is applied and the resulting Ground Reaction Force (GRF) is directed at the hip joint. (left)
- When the torso is tilted backwards, a negative torso torque must be applied to align the GRF with the VPP. (right)

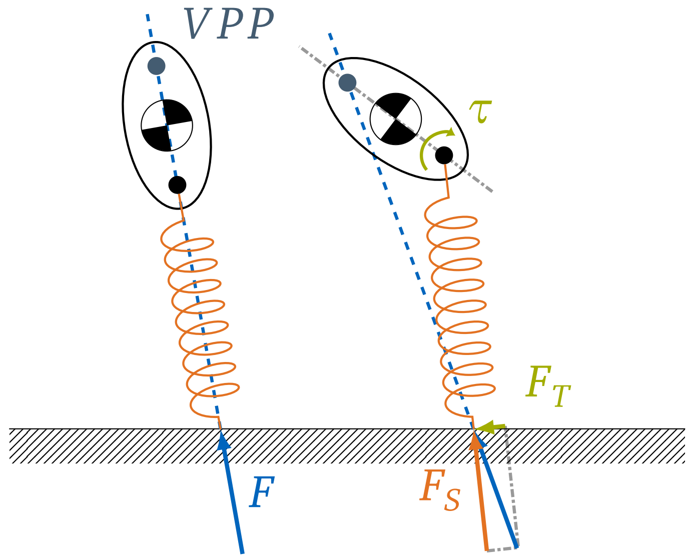
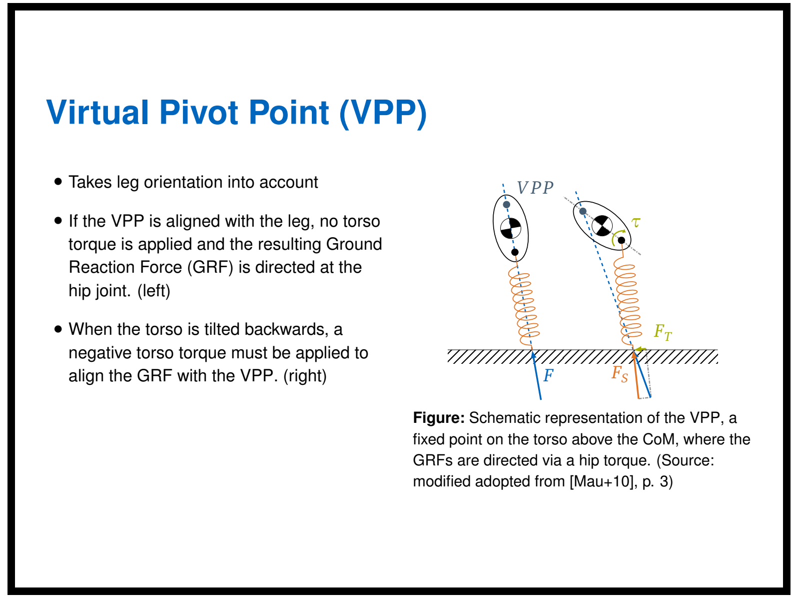


Figure: Schematic representation of the VPP, a fixed point on the torso above the CoM, where the GRFs are directed via a hip torque. (Source: modified adopted from [Mau+10], p. 3)

Notes of Slide 11: Virtual Pivot Point (VPP)

- When GRF always directs at VPP: becomes virtual hinge around which the torso will rotate
- Transforms difficult task of balancing inverted pendulum to system consisting of pendulum suspended from hinge, which is intrinsically stable



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Notes of Slide 12: References I

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Notes of Slide 13: References II

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[Sey+02] Seyfarth, A., Geyer, H., Günther, M., and Blickhan, R. “A movement criterion for running”. In: *Journal of Biomechanics* 35.5 (May 2002), pp. 649–655. DOI: 10.1016/s0021-9290(01)00245-7.

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Glossary I

CoM Center of Mass. 4, 10, 11, 12

CoT Cost of Transport. 10

GRF Ground Reaction Force. 4, 12

H-SLIP Hip Actuated Spring Loaded Inverted Pendulum. 4, 11

SLIP Spring Loaded Inverted Pendulum. 4, 11

VPP Virtual Pivot Point. 4, 12

Notes of Slide 14: Glossary I

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