MIT Cheetah

High speed trot-running (2014)

Group 24

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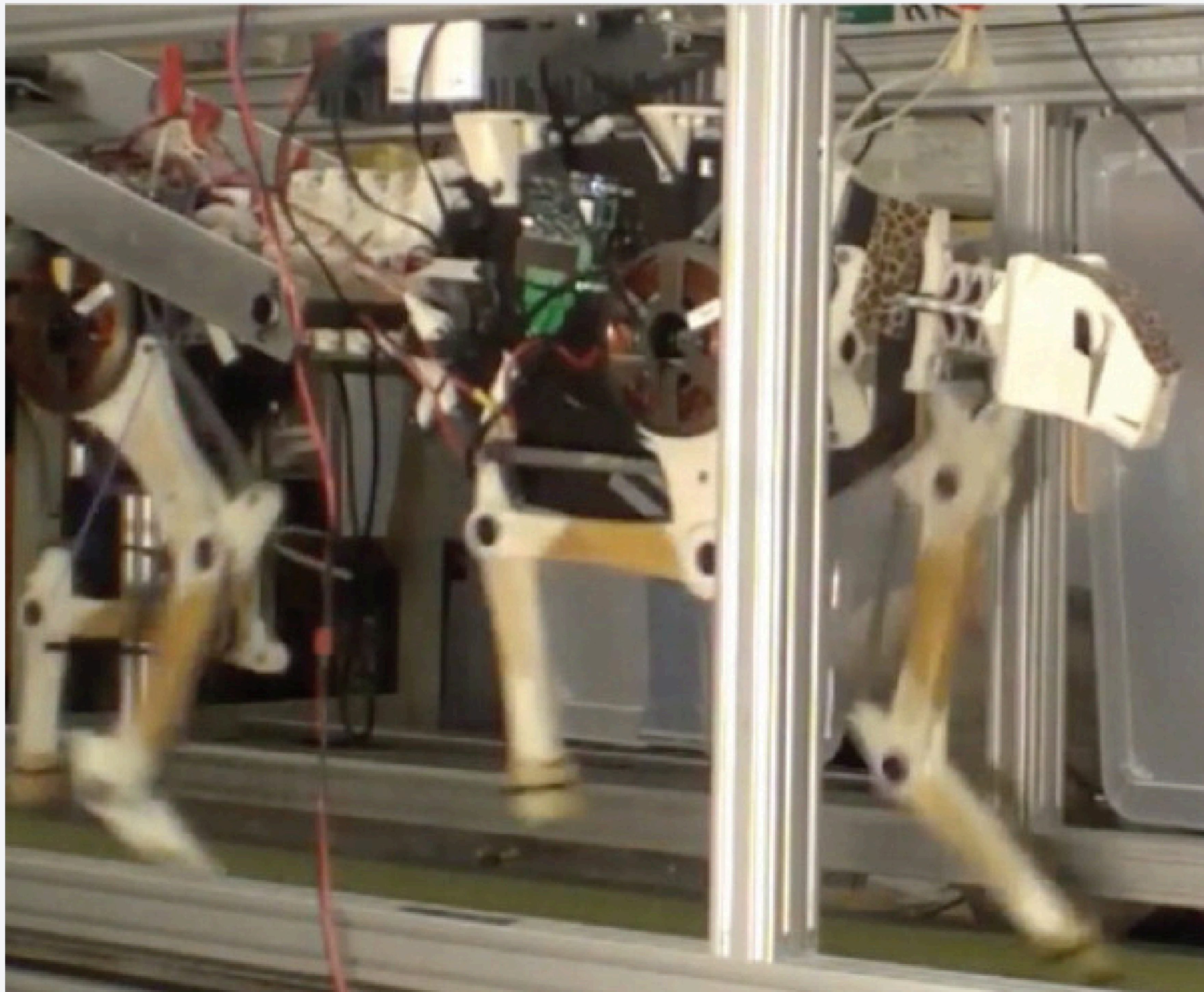
MICRO-507



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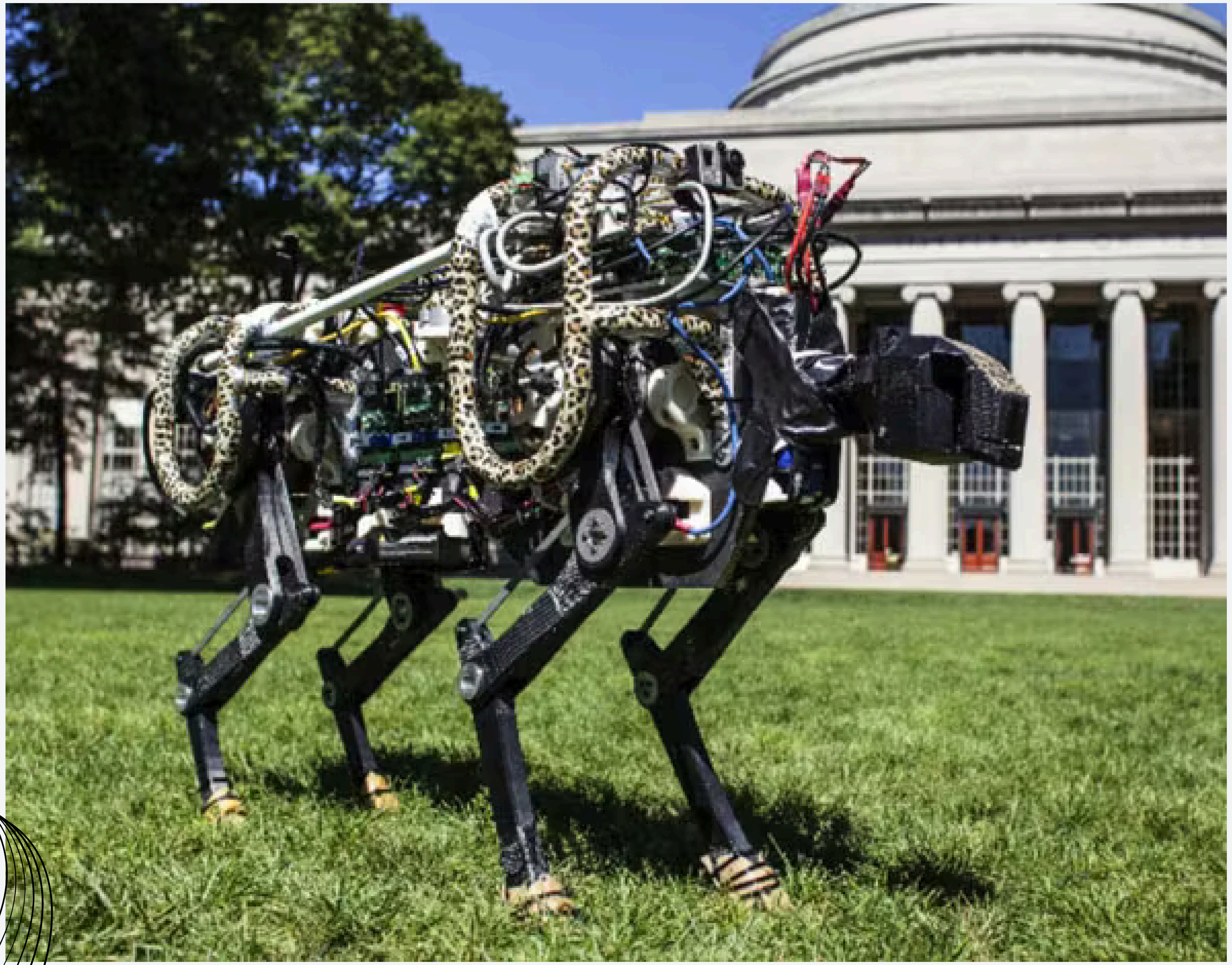

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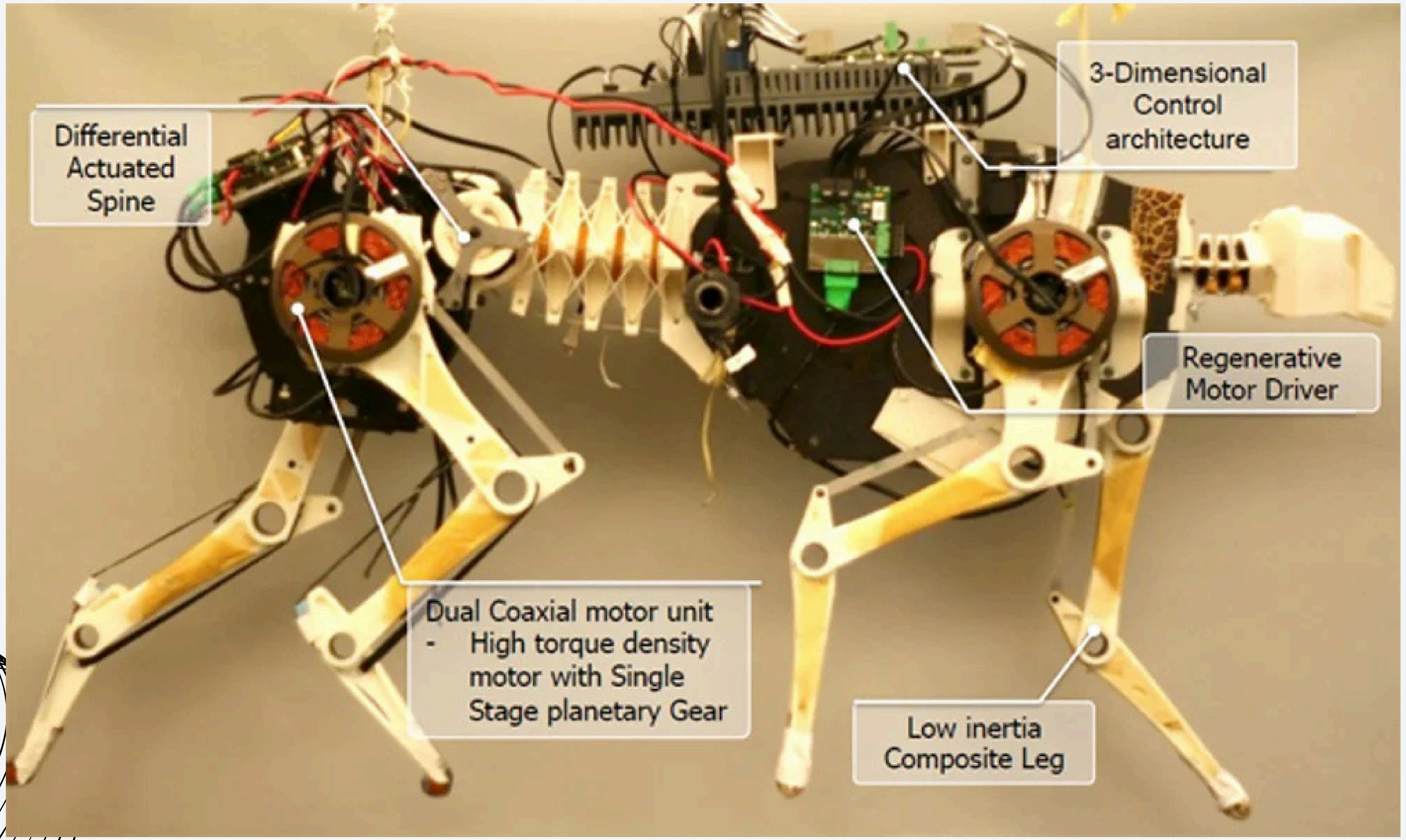
Introduction for MIT Cheetah



01

4 Legged Robot

Developed in MIT since 2013

02

High-Speed running

A speed of 6 m/s
Froud number of 7,34

03

A big Robot

70 pounds cheetah

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Issues in previous research

STABILITY CRITERIA OF LOCOMOTION

Legged locomotion not clearly define

Dependant on sensory feedback

MODULATION OF GAIT-PATTERN

Various types of CPG’s

Adding external feedback

Important to enhance dynamic stability

MODULATION OF GROUND REACTION FORCE

Important for body posture in a desired periodic pattern

Use of compliant force at foots end

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Approach and Outline

1

Low Level leg control

Programmable compliance through proprioceptive force control actuators.
Reflex responses to external forces.
Desired leg impedance on demand.

2

Controller architecture

Combine gait pattern modulator and TD detection as sensory feedback.
Coordination of four legs by tying the time phases of three legs to the reference leg.
The spatial characteristics are independently handled in the leg-trajectory generator.

3

Leg trajectory generator

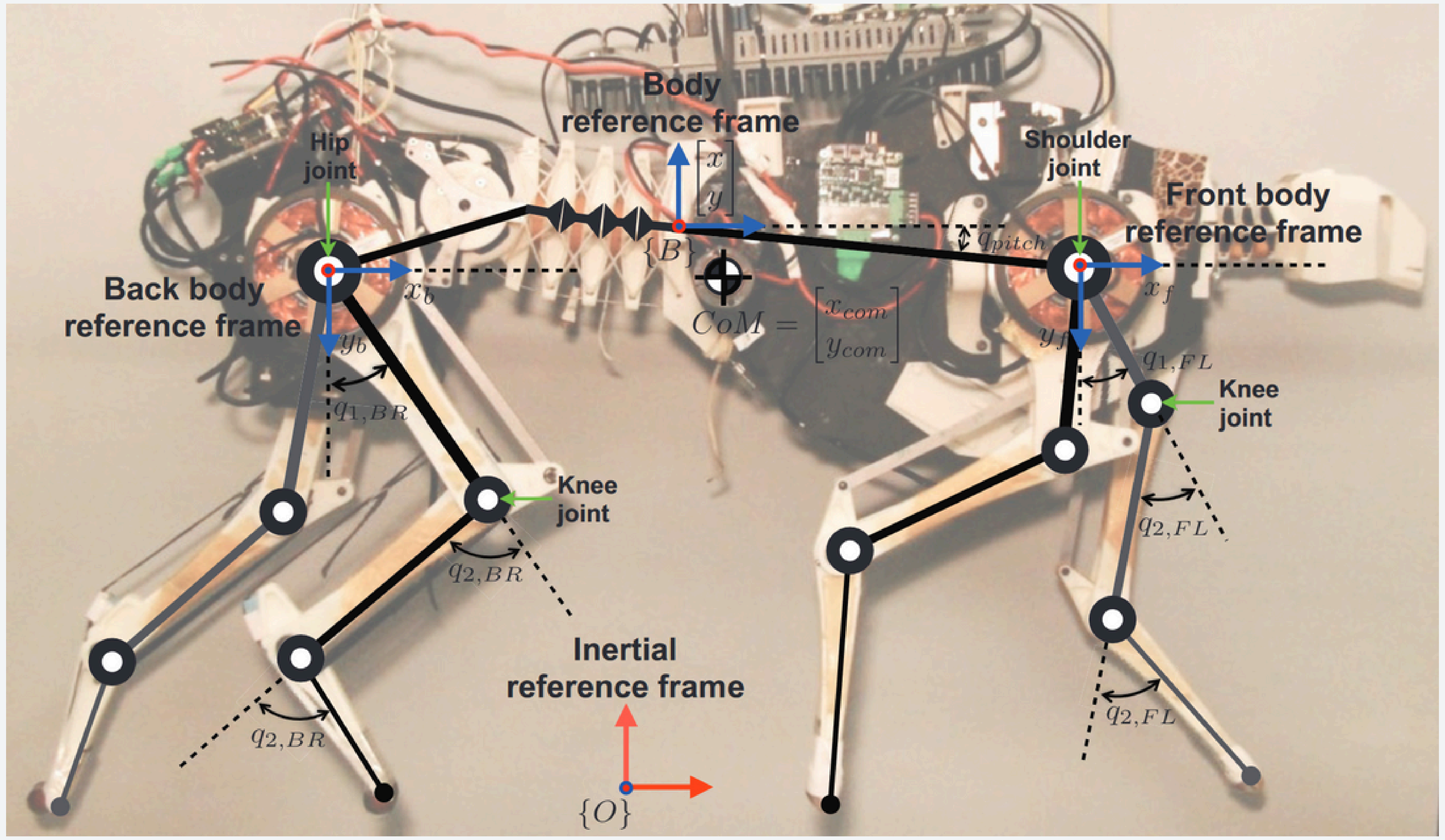
Match the pattern signals from each foot-end position as an instant equilibrium point.
Swing-leg retraction is adjustable to reduce the TD energy losses of running.
Properties of Bézier curves.

Part 2

Modeling of the MIT Cheetah

Assumptions for the Model

- Planar rigid Body
- 11 degrees of freedom
- Three independent coordinates (x,y,q)
- Ground is a rigid half-space
- Friction coefficient constant.



Constrained Equation of Motions

$$D(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = B(q)u + J_c(q)^{\mathrm{T}} F_{\mathrm{ext}} \quad (1)$$

- q is the general coordinates of the Model
- D(q), C(q), G(q) and B(q) are the inertial, coriolis, gravitational torque and input Matrix
- J_c is the Jacobian Matrix of position vectors of each ground contact foot

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Constrained Equation of Motions

$$\Phi(q) = 0_{h\times 1} \quad \dot{\Phi}(q) = 0_{h\times 1} \qquad (2)$$

$$\ddot{\Phi}(q) + 2\alpha\dot{\Phi}(q) + \beta^2\Phi(q) = 0 \qquad (3)$$

- Holonomic equality constraints to solve acceleration q¨ and F
- Baugmarte’s stabilization method is introduce to inihibit violation constraint du to numerical drift

Constrained Equation of Motions

$$\begin{bmatrix} D(q) & -J_c^{\mathrm{T}}(q) \\ J_c(q) & 0_{2\times N_c} \end{bmatrix} \begin{bmatrix} \ddot{q} \\ F_{\mathrm{ext}} \end{bmatrix} = \begin{bmatrix} -C(q,\dot{q})\,\dot{q} - G(q) + B(q)\,u \\ -\dot{J}_c(q)\,\dot{q} - 2\alpha\dot{\Phi} - \beta^2\Phi \end{bmatrix} \tag{4}$$

- Associating equation 2 and 3 give us this system
- Alpha and Beta are the Baumgarte parameters

Impact Map

$$q^{+} = q^{-} \tag{5}$$

$$D(q)\,\dot{q}^{+} - D(q)\,\dot{q}^{-} = J_c(q)^{\mathrm{T}} \int F_{\mathrm{ext}}\mathrm{d}t \tag{6}$$

$$\dot{\Phi}(q) = 0_{h\times 1} \tag{7}$$

- When legs touch down system state undergo an abrupt change du to large impulsive force.

- The generalized velocities after impact qdot+ can be solve using this system of equation.

Coulomb friction Model

$$\Phi(q) = \begin{bmatrix} p_c^{NS}(q) \\ p_{c,n}^{S}(q) \end{bmatrix} - \begin{bmatrix} p_c^{NS}(q_0) \\ p_{c,n}^{S}(q_0) \end{bmatrix} = \begin{bmatrix} 0_{2N_{NS}\times 1} \\ 0_{N_S\times 1} \end{bmatrix} \quad (8)$$

$$\dot{\Phi}(q) = \frac{\partial}{\partial q} \begin{bmatrix} p_c^{NS}(q) \\ p_{c,n}^{S}(q) \end{bmatrix} \dot{q} = \begin{bmatrix} J^{NS}(q) \\ J_n^{S}(q) \end{bmatrix} \dot{q} = \begin{bmatrix} 0_{2N_{NS}\times 1} \\ 0_{N_S\times 1} \end{bmatrix} (9)$$

$$J_c^{\mathrm{T}} F_{\mathrm{ext}} = \begin{bmatrix} J^{NS} \\ J_n^{S} + \mathrm{M} J_t^{S} \end{bmatrix}^{\mathrm{T}} F_{\mathrm{ext}} \quad (10)$$

- Trying to prevent slipping of the robot
- Coulomb law :
  Ft <= μFn
- “non-slip ground contact foot” (NS)
- “slip ground-contact foot” (S)
- M is the diagonal Matrix of μ

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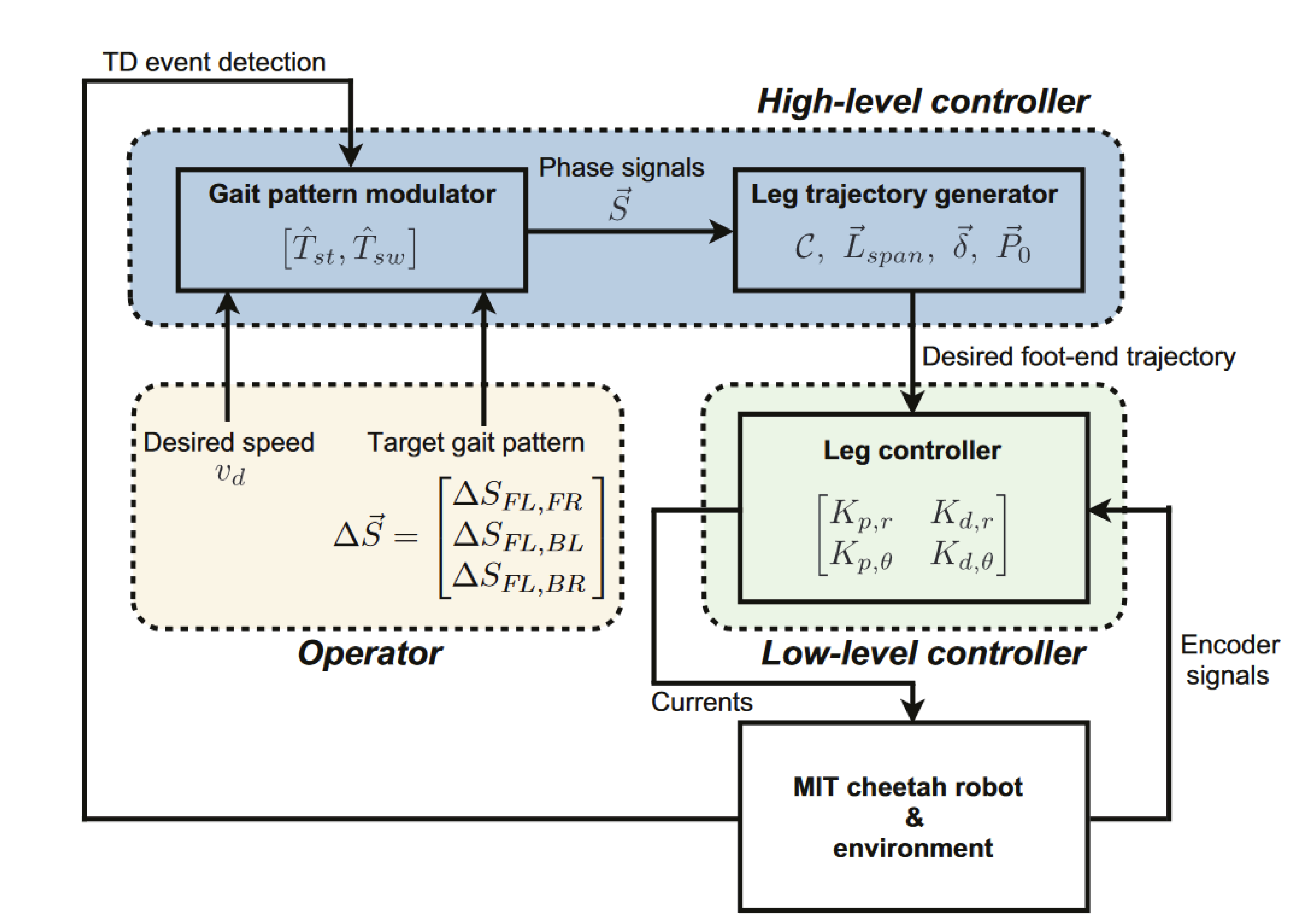
Part 3

Quadruped locomotive control framework

Overall Structure of the Locomotive Control Framework



Hierarchical structure composed of three main control elements:

1. (High Level) Gait Pattern Modulator
2. (High Level) Leg Trajectory Generator
3. (Low level) Virtual Leg Compliance impedance control

Gait Pattern Modulator with Proprioceptive Sensory Feedback

- **High level control** which achieves a target velocity and gait-pattern by coordinating the four limbs with phase signals

- The controller imposes phase lag between the legs to temporally coordinate them to achieve a certain gait pattern, with each specific gait pattern having their own fixed phase signals

Phase lag vector to achieve a galloping gait

$$\Delta\vec{S}_{\text{gallop}} = \begin{bmatrix} \Delta S_{\text{FL,FR}} \\ \Delta S_{\text{FL,BL}} \\ \Delta S_{\text{FL,BR}} \end{bmatrix}_{\text{gallop}} = \begin{bmatrix} 0.2 \\ 0.55 \\ 0.75 \end{bmatrix}$$

Gait Pattern Modulator with Proprioceptive Sensory Feedback

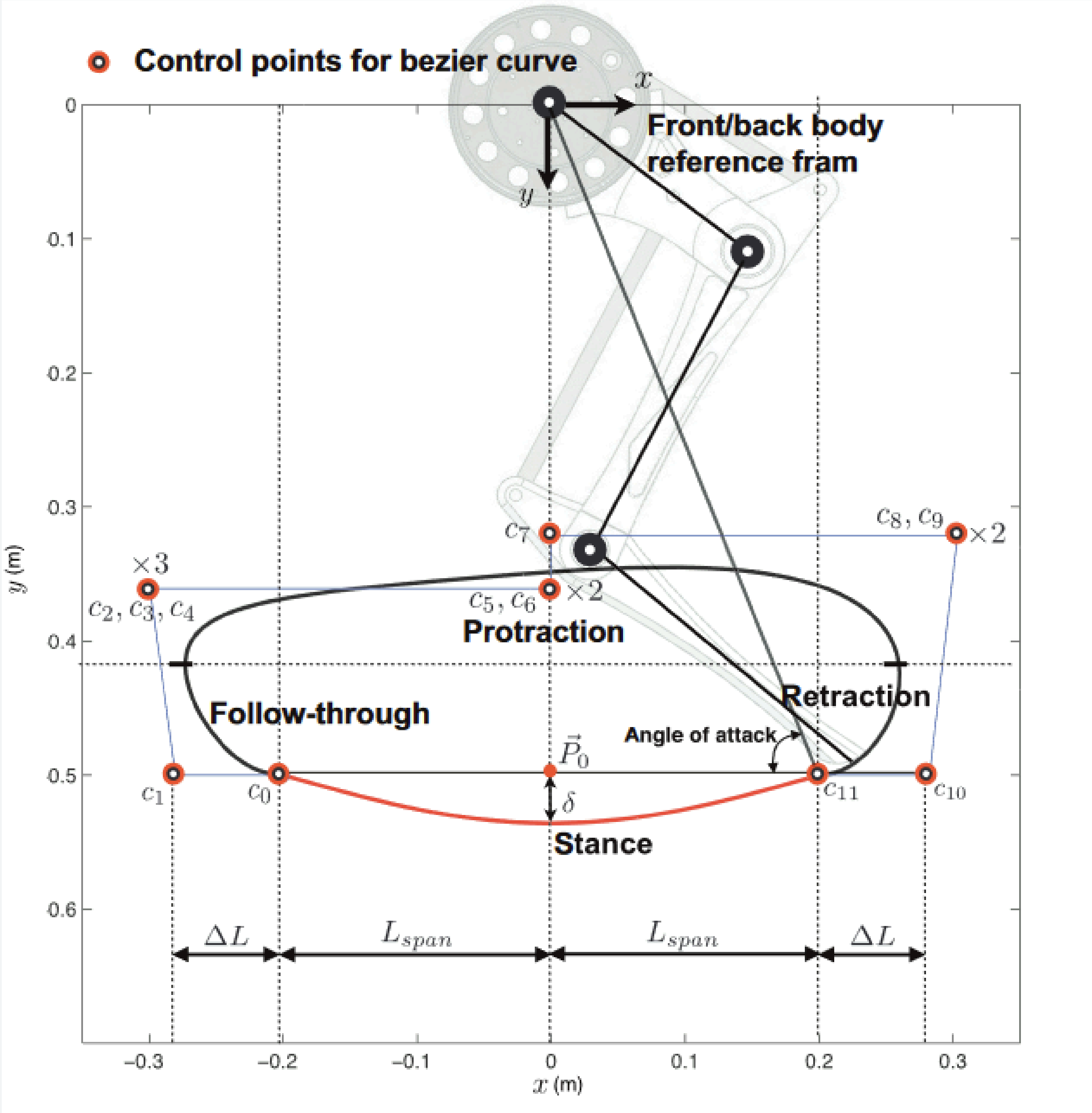
- The **phase signals** have to be synchronized with the environment so that it is properly commanded when the legs are touching the ground or swinging.

- This is achieved by detecting Touch-down (TD) and Lift-off (LO) events of a **reference leg**, and the commanding phase lags to the other legs from the reference

- Touch-down and Lift-off events are normally recorded by placing force sensors at the foot-ends, but thanks to the **low mechanical impedance** of the **proprioceptive actuators**, these events are detected by sensing abrupt forces in the torque command.

Leg Trajectory Generator

- The **leg trajectory generator** transforms the **phase signals** from the gait pattern modulator to the **desired trajectories** for each foot end.
- The **swing phase** and **stance phase** trajectories are designed separately for different purposes, position-control and compliance-force control



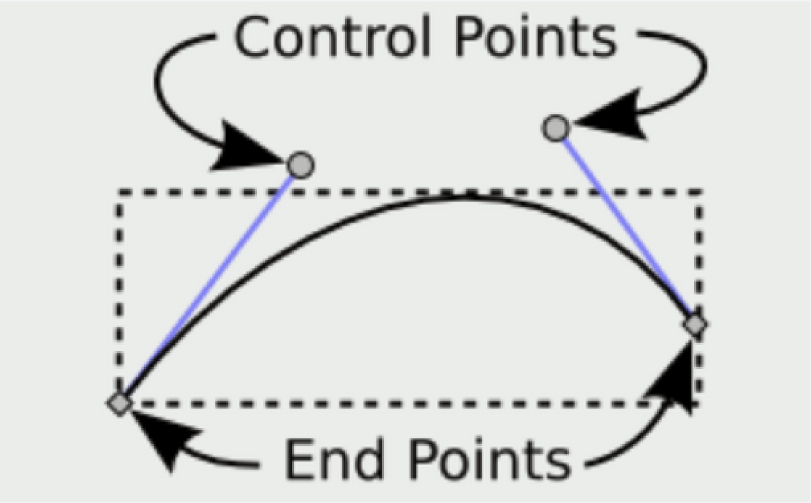
In red: Stance Phase Leg Trajectory

In black: Swing Phase Leg Trajectory

Leg Trajectory Generator

Swing Phase Leg Trajectory Design

- The design objective of the swing-phase trajectory is to protract a leg with sufficient ground clearance to avoid obstacles
- A smooth trajectory is required to avoid sudden movements or jerking when tracking, which leads to instability
- In this paper the swing phase trajectory is made from 12 control points
  Bezier Curve



Bezier Curve (Think making curves in Illustrator)

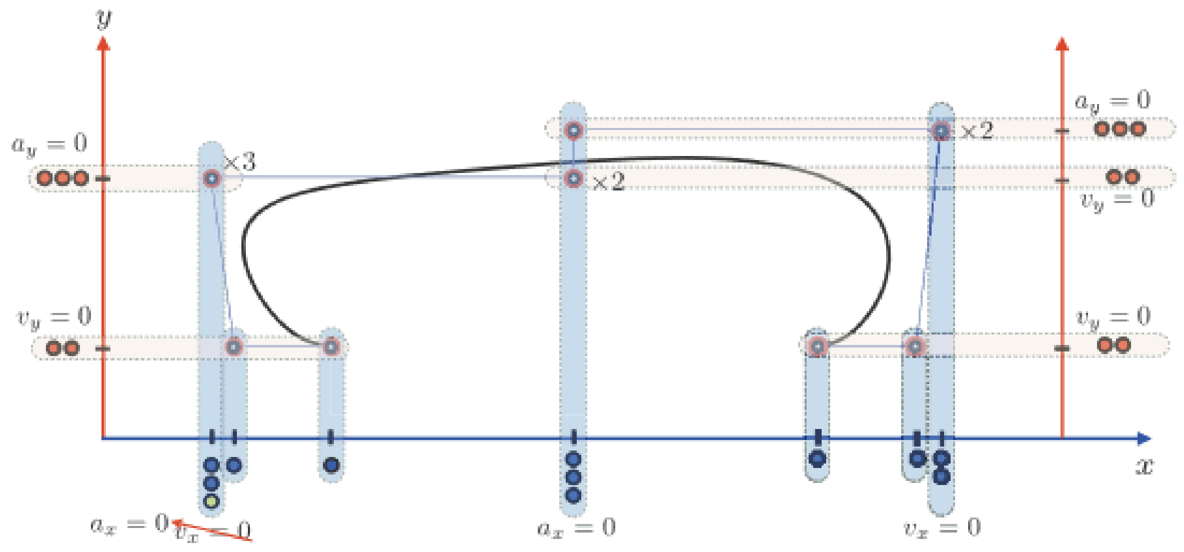


Fig. 7. Separation of twelve control points of Bézier curve for swing-phase trajectory into vertical direction and horizontal direction.

Leg Trajectory Generator

Stance Phase Leg Trajectory Design

- The stance-phase control of each leg involves ground interaction which is at the core of quadruped locomotion
- To achieve vertical periodic motion of the COM, one must satisfy the equation:

$$mgT_{\text{stride}} = \sum_{\text{contact}} \int_0^{T_{\text{st}}} F_{\text{ext}}^n(t)\ dt$$

- During a single **stride period**, one must produce equivalent work with the **leg impulses** to counteract the work of the **quadruped weight**

Leg Trajectory Generator

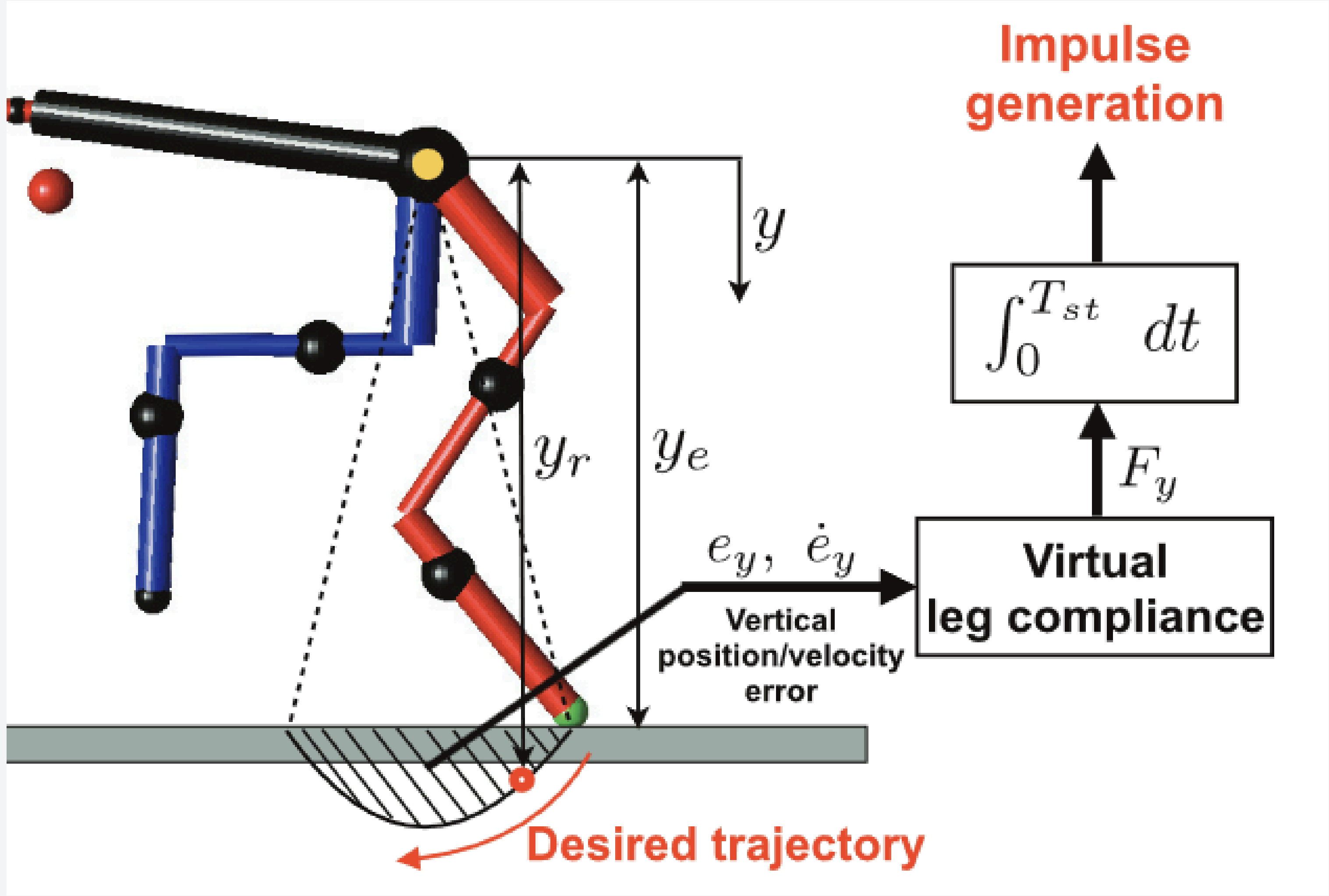
Stance Phase Leg Trajectory Design

- Direct force control is challenging due to non-linearities in the system and high required precision in pose estimation.
- Force control is done only by measuring the joint positions with encoders and exploiting the **Equilibrium Point Hypothesis**
- This **Equilibrium Point Hypothesis** states that animals might exert force on the environment by controlling the equilibrium point of their limbs' virtual compliant system to have a **penetration depth** into a contact surface.
- The difference between the actual position of the foot and the penetrating equilibrium point position would allow to generate the appropriate Ground Reaction Forces (GRF) without complicated computations

Leg Trajectory Generator

Stance Phase Leg Trajectory Design

- The stand-phase trajectory should be the trajectory of the legs **equilibrium points** of a **virtual compliant leg.** (dips under the ground)
- The impedance control generates reaction forces at the foot-end proportional to the **displacement/ velocity** errors of the **equilibrium point trajectory** relative to the **real leg positions**.
- For a fixed virtual impedance, one can modulate the vertical ground reaction forces by varying the **penetration depth** of the equilibrium point trajectory



Leg Trajectory Generator

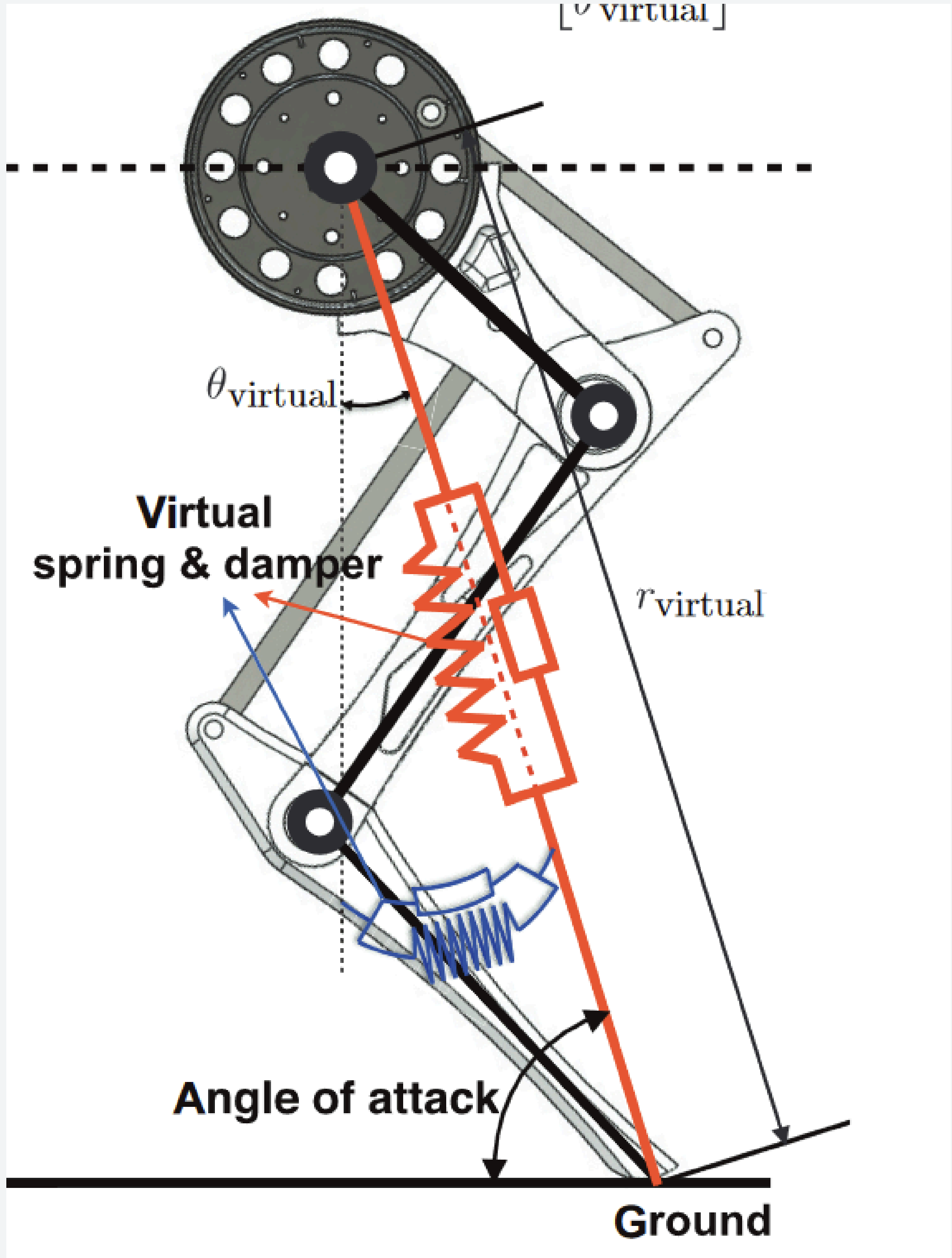
Low Level Individual Leg Controller

- Impedance control in each leg on the actuators to provide **virtual compliance** during the **stance phase,** and to accomplish **motion tracking** during the **swing phase**

- Virtual Leg compliance is realized as a muscle's **viscoelastic** model; the virtual leg is defined as the straight line in **polar coordinates** (r,θ) between the hip and the ground contact point, with virtual **spring and damper** systems acting on **r** and **θ** separately

- Very fast sample rate for the **low level control loop**

- Foot-end positions and velocities for motion tracking are computed using the legs Fwd kinematics and Jacobian w/ respect to the shoulder/hip.



Part 4

Simulation results

Simulation Results

- Instead of following the trajectories of every state of the robot, we evaluate the **stride-to-stride** evolution to check stability

- Steady state **periodic locomotions** and stable **Limit Cycles** are achieved for various speeds (3.5, 4.5 and 5.5 m/s)

- Simulations of multiple strides in the presence of initial large perturbations shows sufficient basins of attraction of the limit cycles, which implies **self stability**

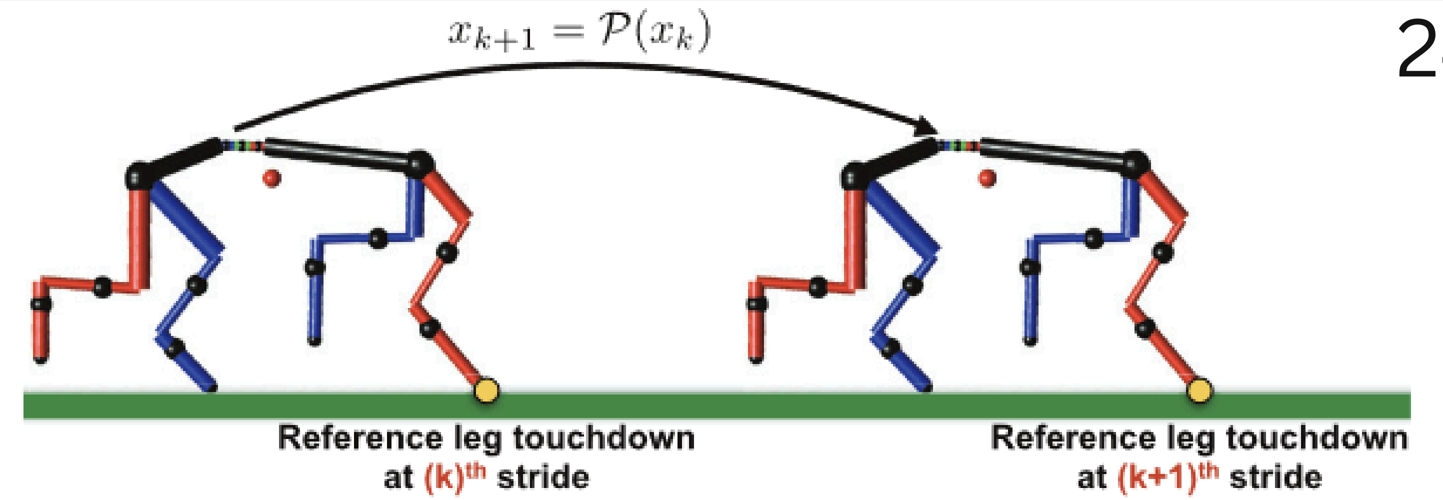
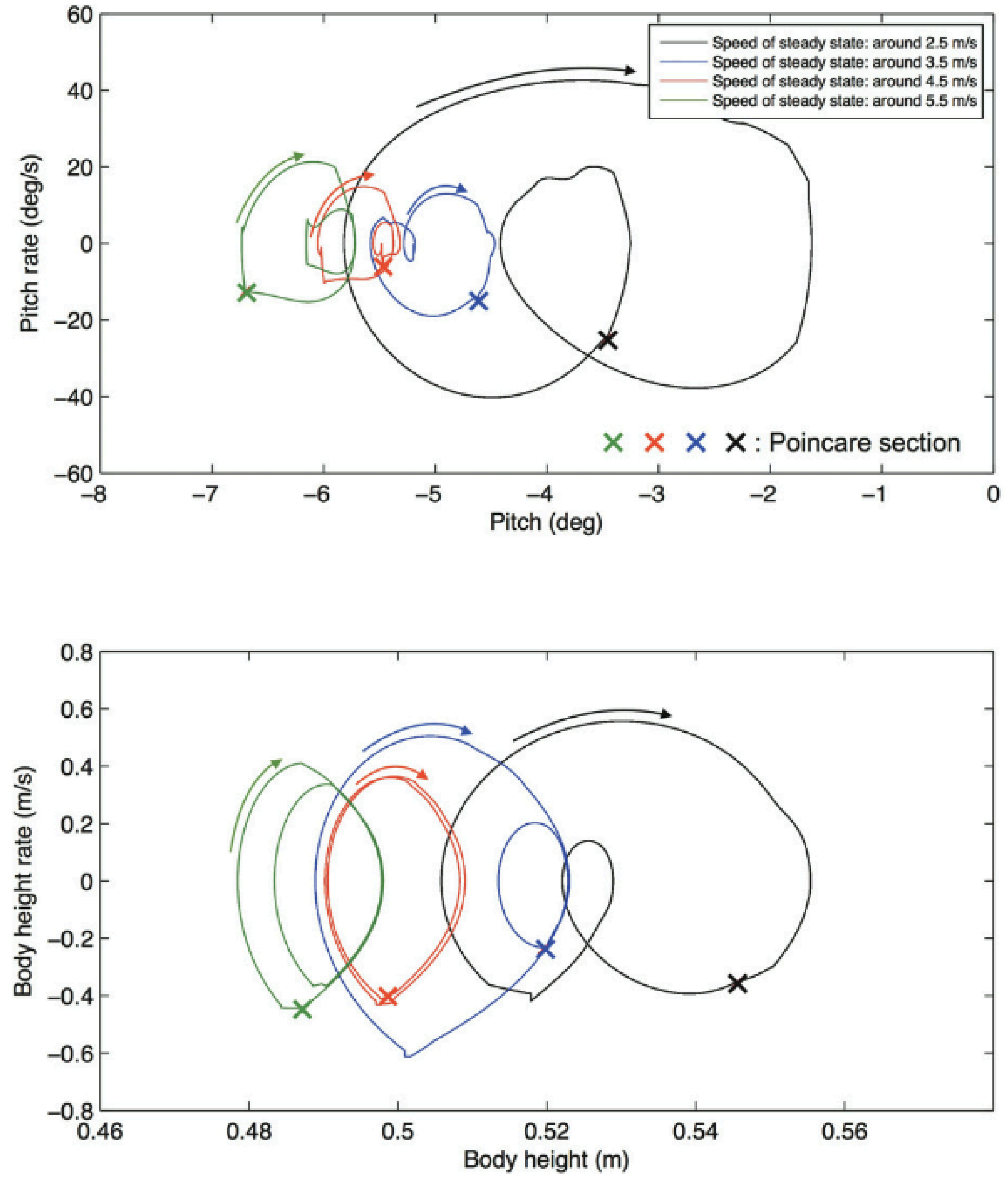


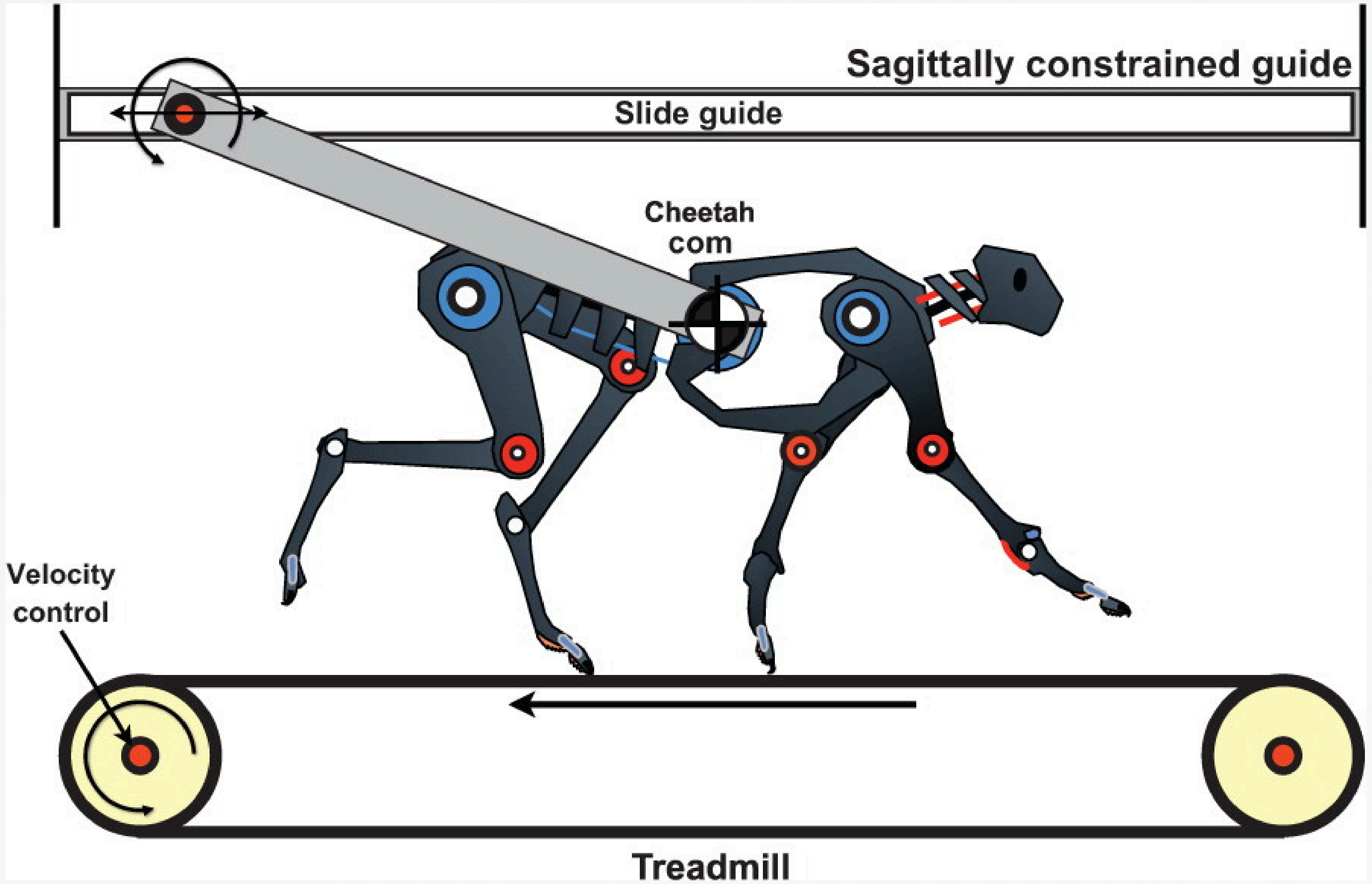
Fig. 12. Stride-to-stride return map to analyze steady-state motion and local orbital stability of the limit cycle. The instants at which the reference leg touches down to the ground define the Poincarè section.



Part 5

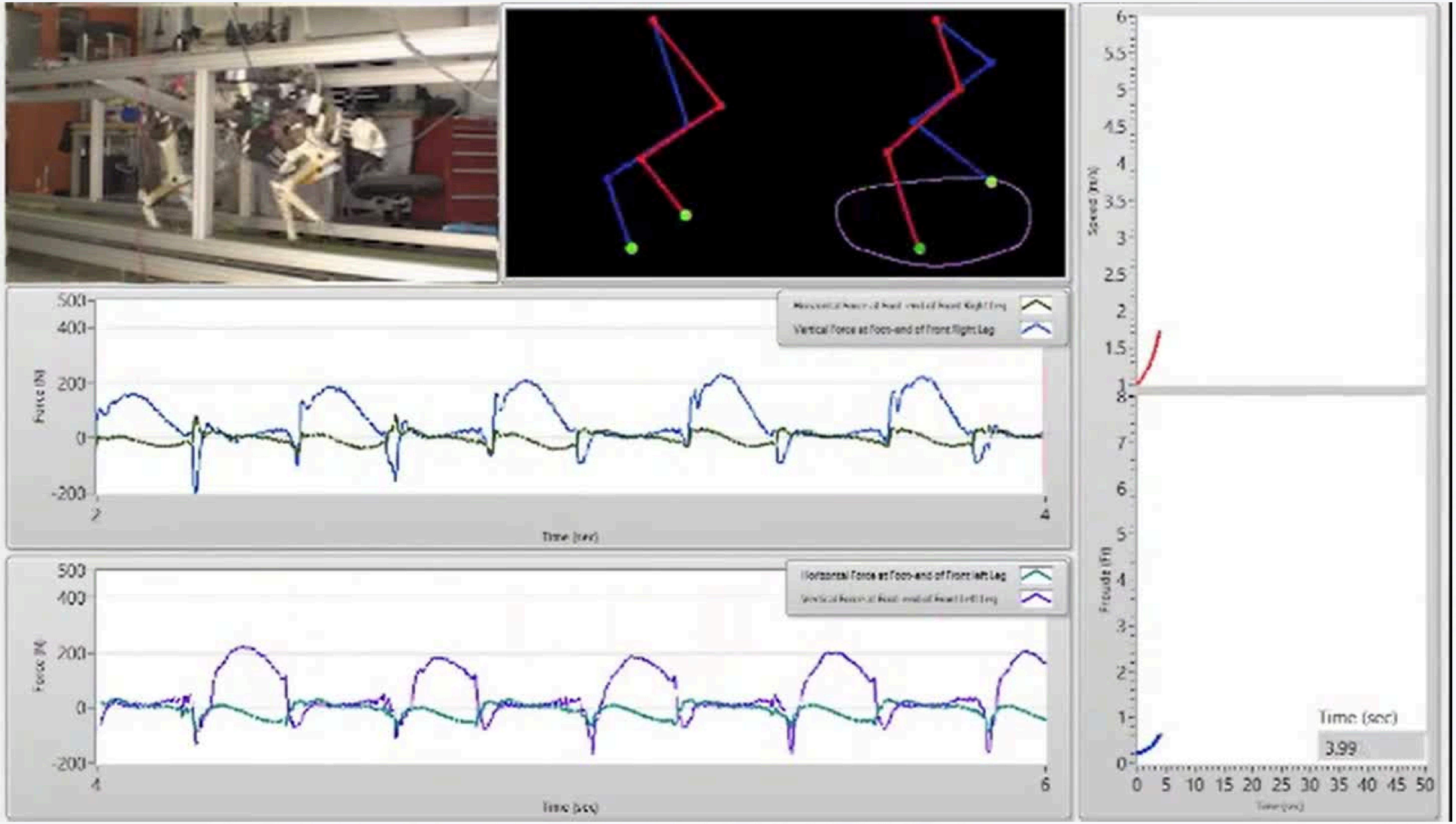
Experiments

Experimental Setup



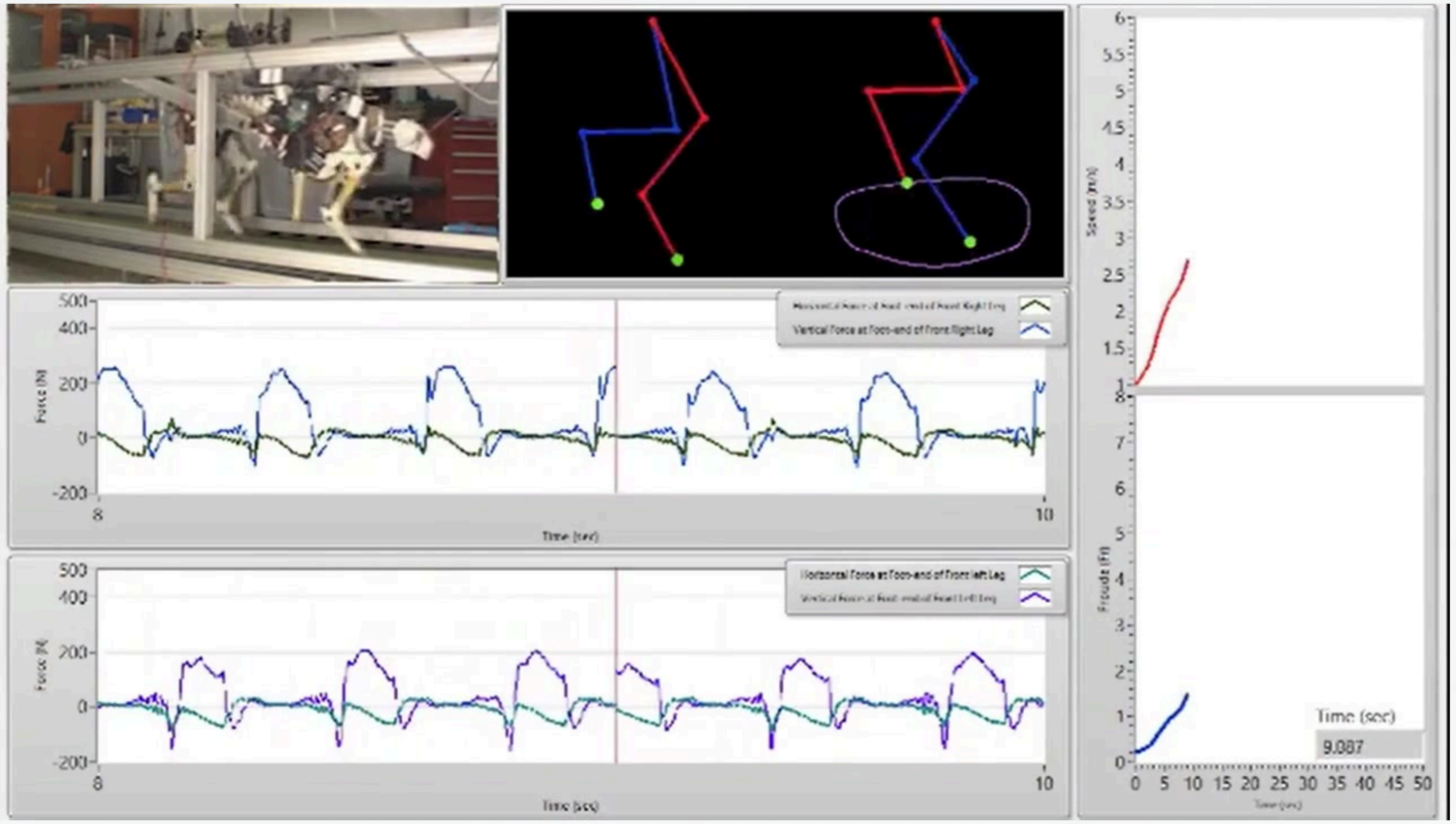
- Sagittally constrained
- Maximum speed:
  6 m/s
- Sensory feedbacks:
  positional data for each leg joint

Results



Yuta

Results



- Stable running was observed
- Walking-running transition at 2.2 m/s
- Trot-to-gallop gait transition was unstable

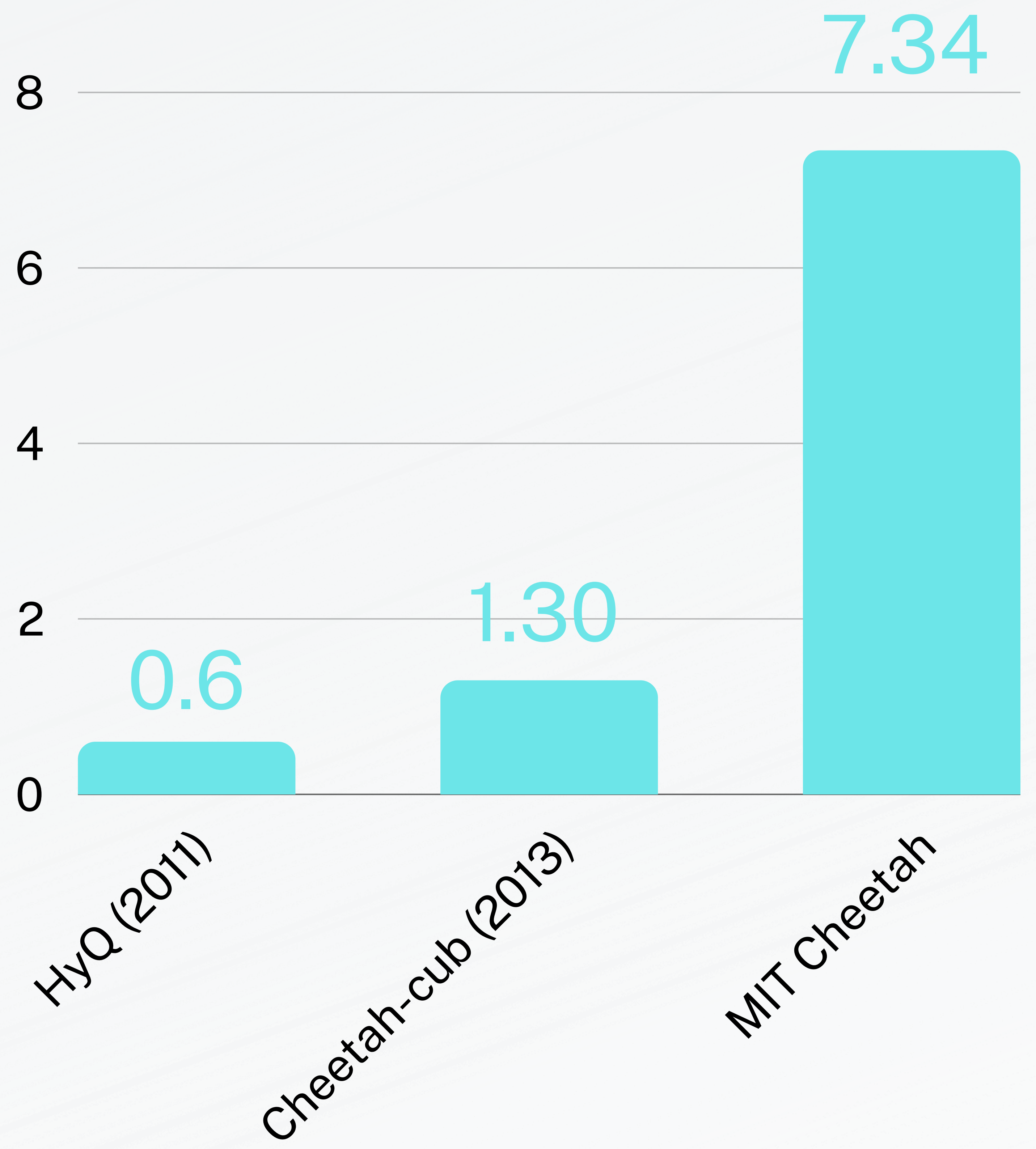
Part 6

Discussion and Conclusion

Comparison with Other Robots

Froude number $$Fr = \frac{v^2}{gh}$$

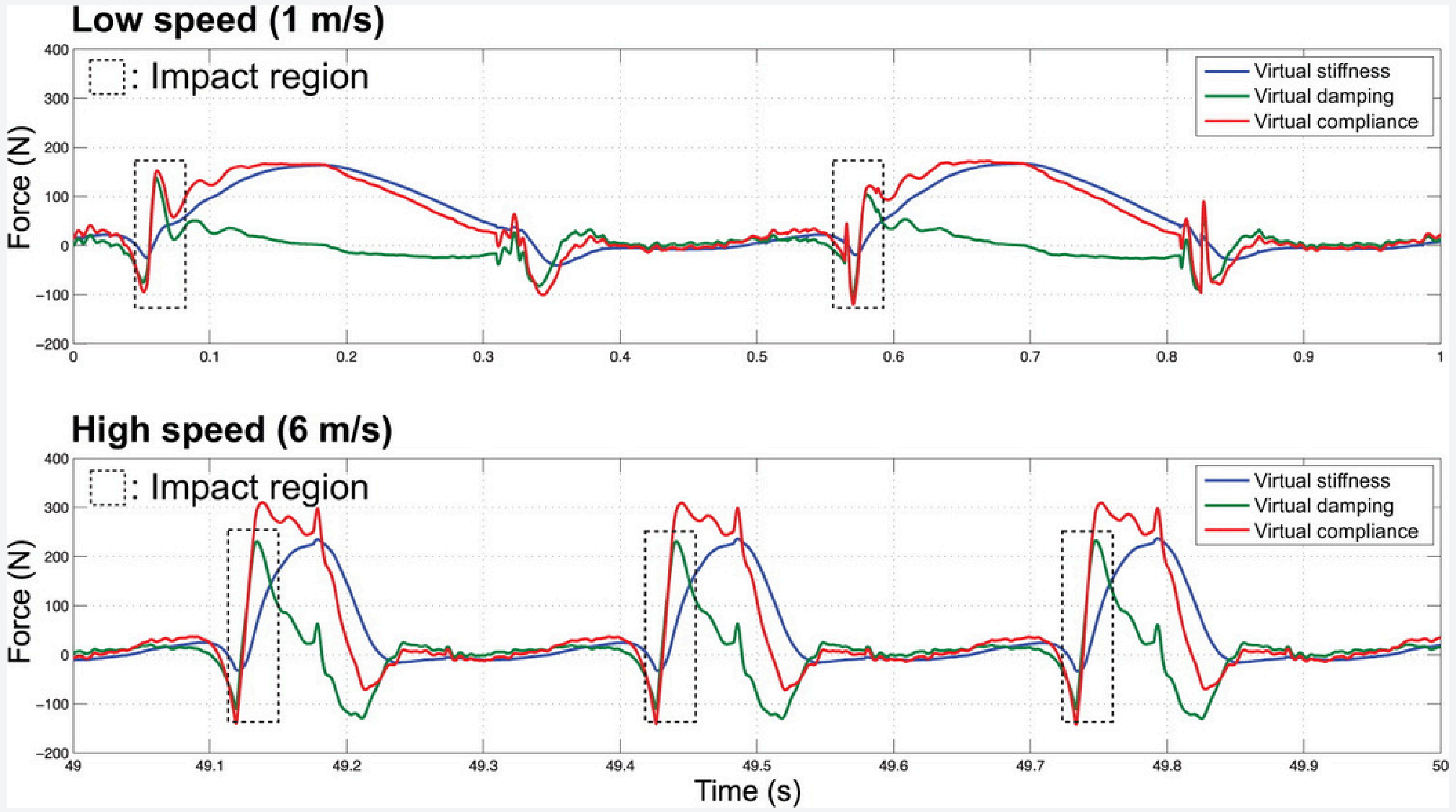
- Higher than previous quadruped robots
- Higher than animals' trot gait



Contribution of Virtual Damping

- Virtual damping creates high forces at the touch down event to deal with ground impact

- The contribution increases when the speed increases and the duration of stance phase decreases



Pros and Cons

Pros

- Efficient and stable high-speed locomotion
- Innovative hierarchical control architecture
- Effective use of simulation for parameter tuning

Cons

- Sagittally constrained
- Incomplete gait transitions
- Lack of testing on complex terrains

Citations

323 citations (23.11.2024)

- Kyunam Kim et al., A bipedal walking robot that can fly, slackline, and skateboard.Sci. Robot.6, eabf8136(2021). DOI: 10.1126/scirobotics.abf8136
- G. Bellegarda and A. Ijspeert, "CPG-RL: Learning Central Pattern Generators for Quadruped Locomotion," in IEEE Robotics and Automation Letters, vol. 7, no. 4, pp. 12547-12554, Oct. 2022, doi: 10.1109/LRA.2022.3218167
- Alexander Badri-Spröwitz et al., BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching.Sci. Robot.7,eabg4055(2022). DOI: 10.1126/scirobotics.abg4055
- M. Shafiee, G. Bellegarda and A. Ijspeert, "Puppeteer and Marionette: Learning Anticipatory Quadrupedal Locomotion Based on Interactions of a Central Pattern Generator and Supraspinal Drive," 2023 IEEE International Conference on Robotics and Automation (ICRA), London, United Kingdom, 2023, pp. 1112-1119, doi: 10.1109/ICRA48891.2023.10160706

Possible Exam Questions

- What’s the purpose of low impedance proprioceptive actuators when designing legged robots?
  Answer: (refer to slide 16)

- What’s the Equilibrium Point Hypothesis? Give an example of how it’s exploited to facilitate quadruped locomotion
  Answer: (refer to slides 20-22)

THANK YOU!