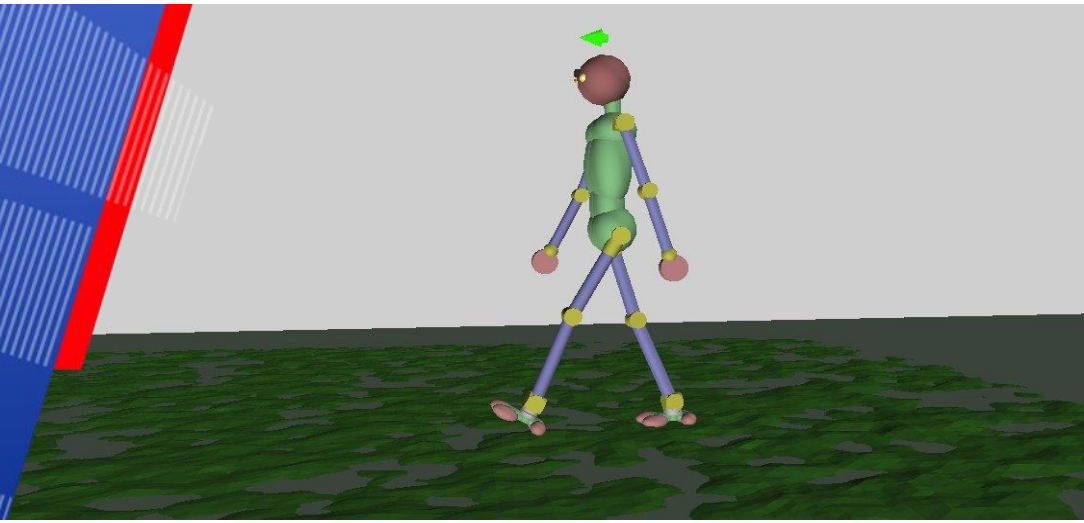
Optimization of the behavior system for controlling bipedal locomotion against external disturbances



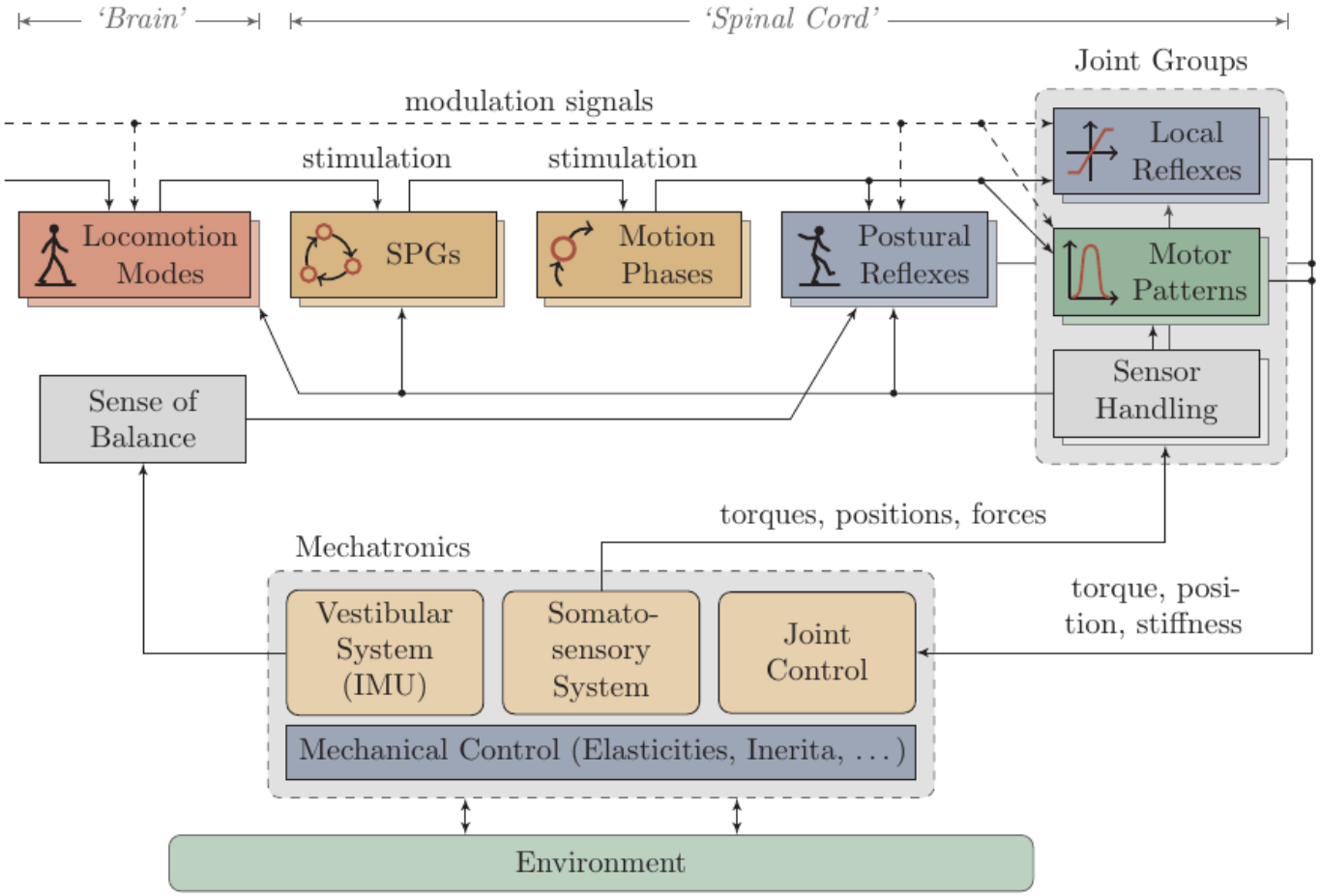
Steffen Schütz, Jie Zhao
Robotics Research Lab
Department of Computer Science
University of Kaiserslautern, Germany

Outline

- Overview Behavior-Based Control Architecture
- Disturbance Estimation and Compensation while Standing
- Strategies for Push Recovery while Walking

Overview Behavior-Based Control Architecture

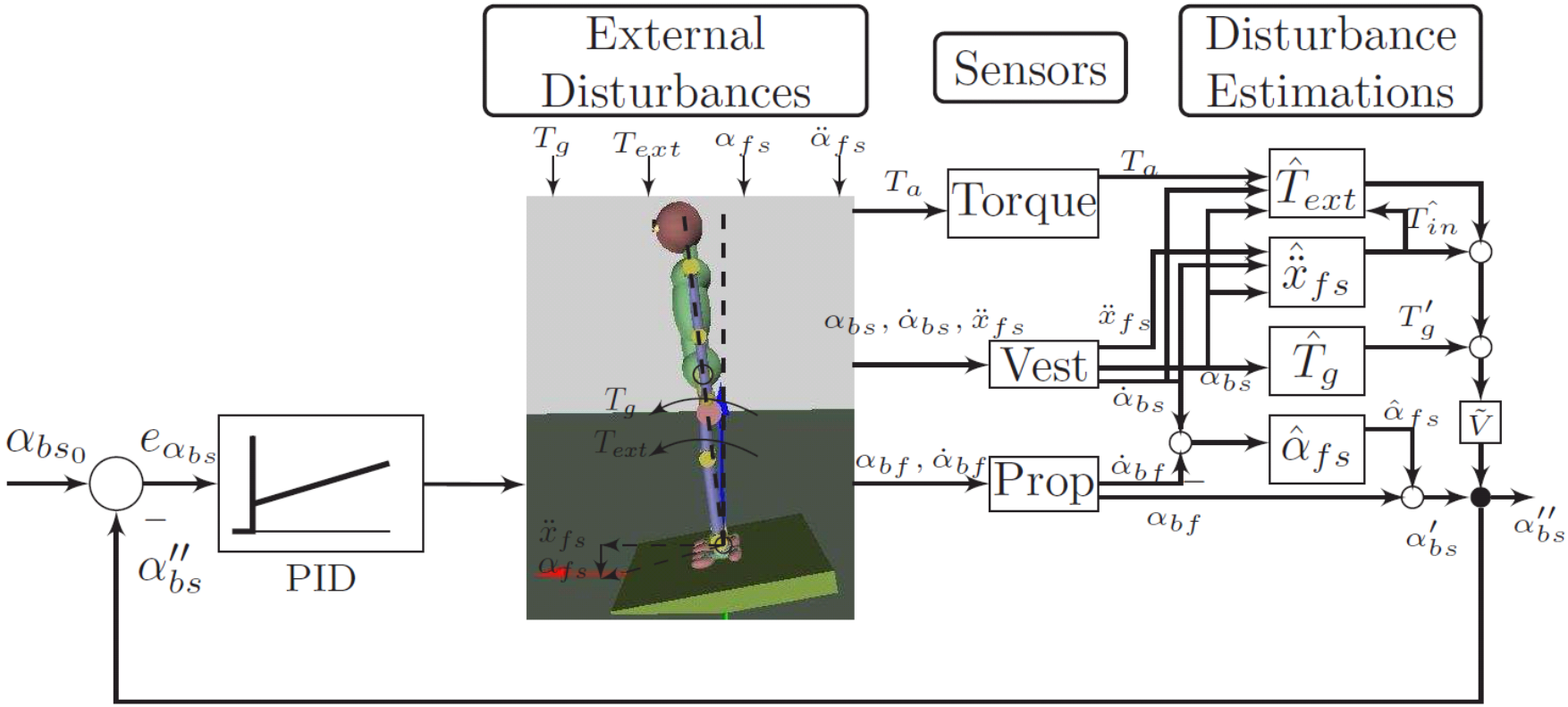
Behavior-Based Control Architecture



[Proetzsch10 , Luksch10]

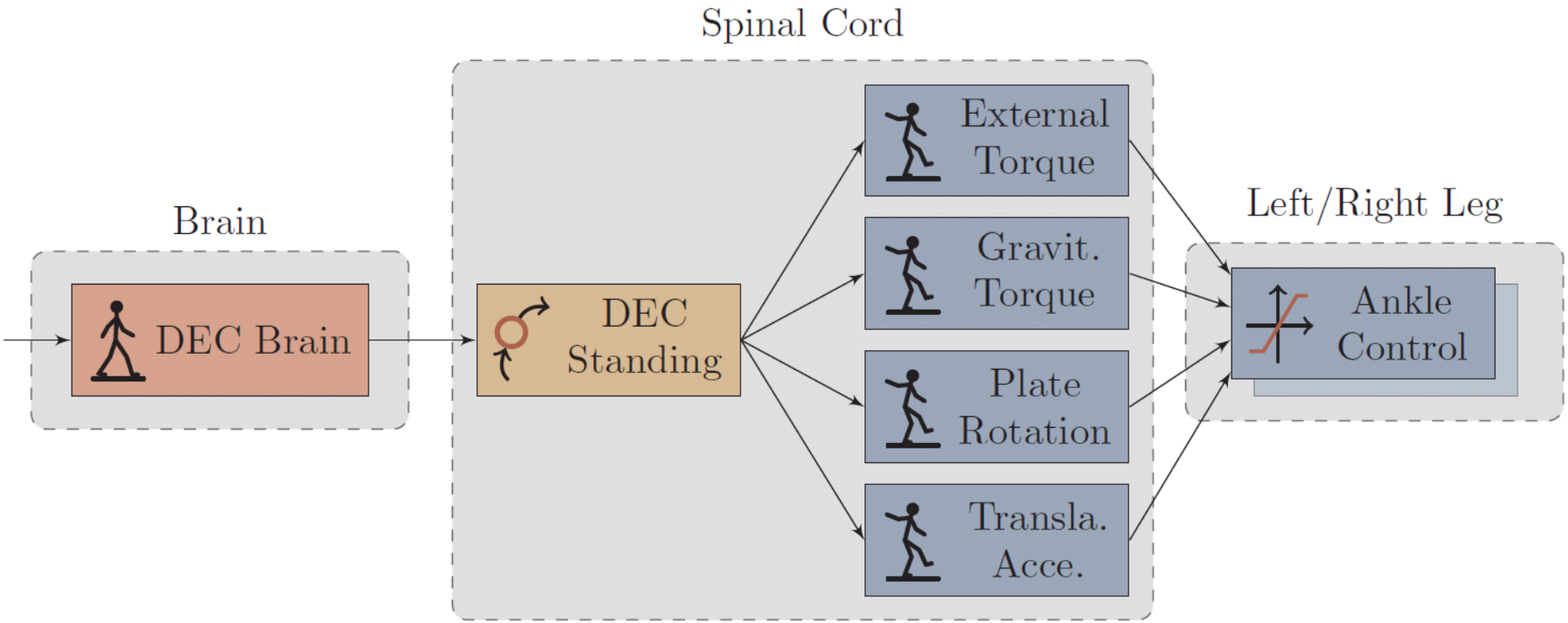
Disturbance Estimation and Compensation (DEC) while Standing

Disturbance Estimation and Compensation (DEC)

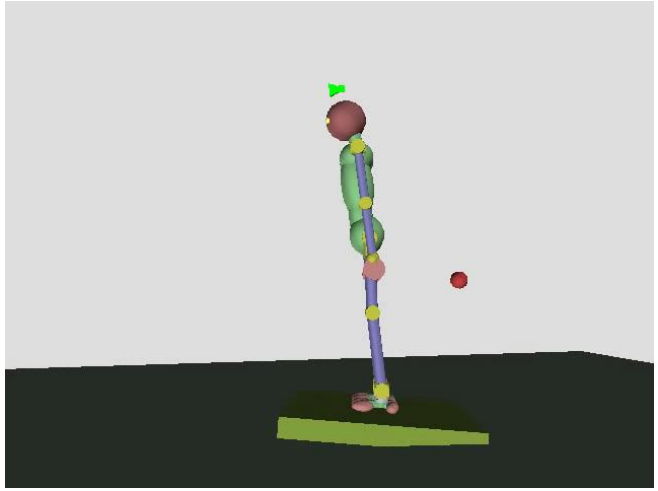


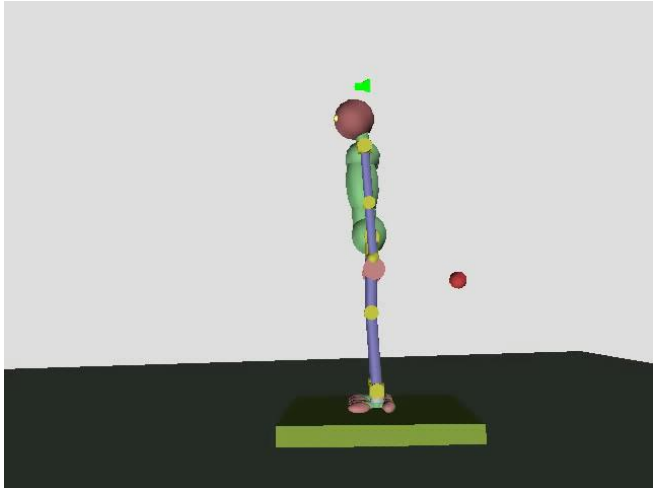
[Mergner10]

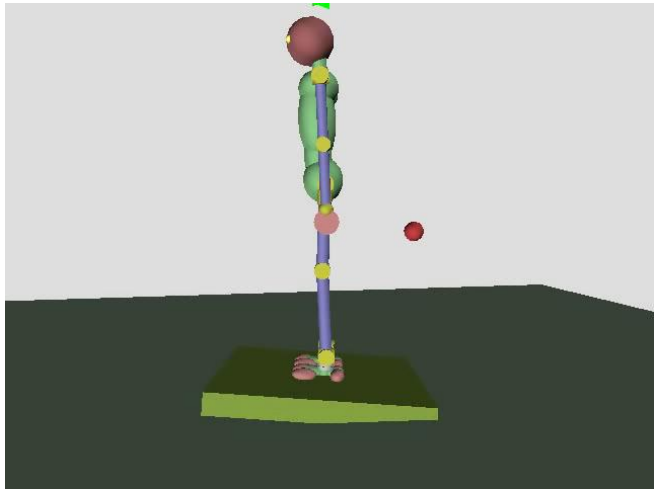
DEC – Implementation/Integration

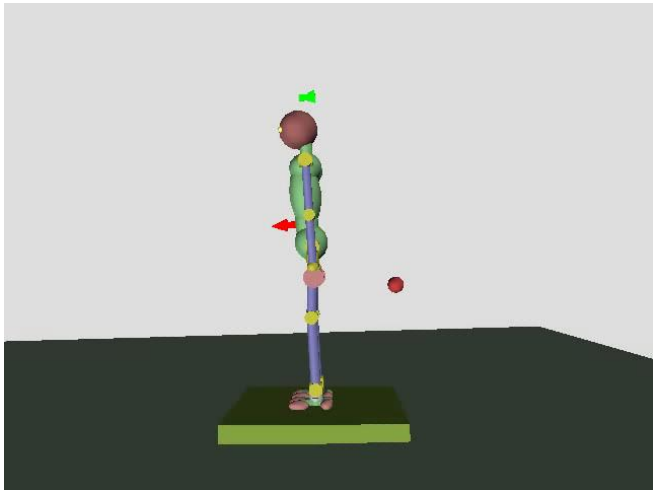


DEC - Experiments

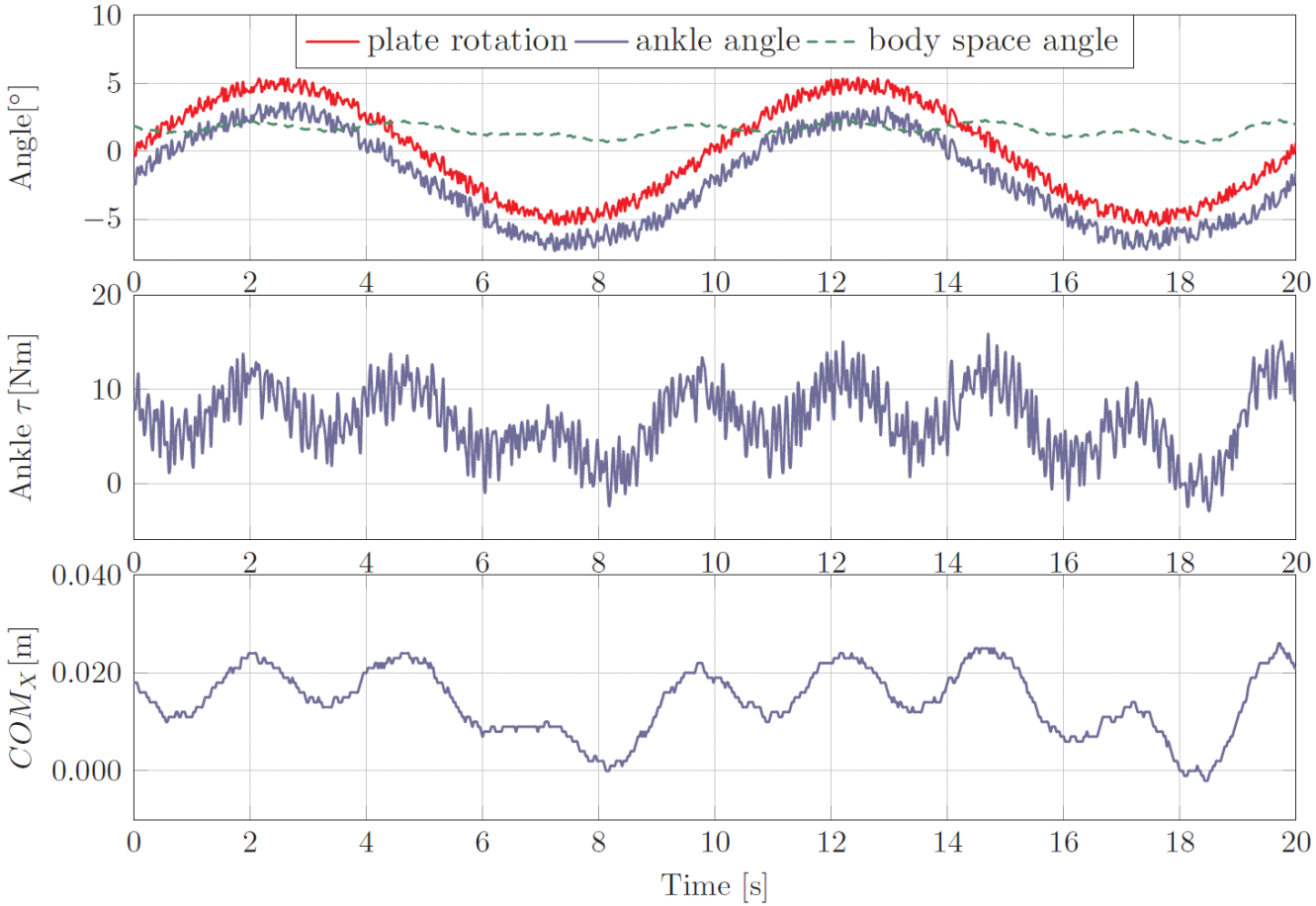








DEC - Results



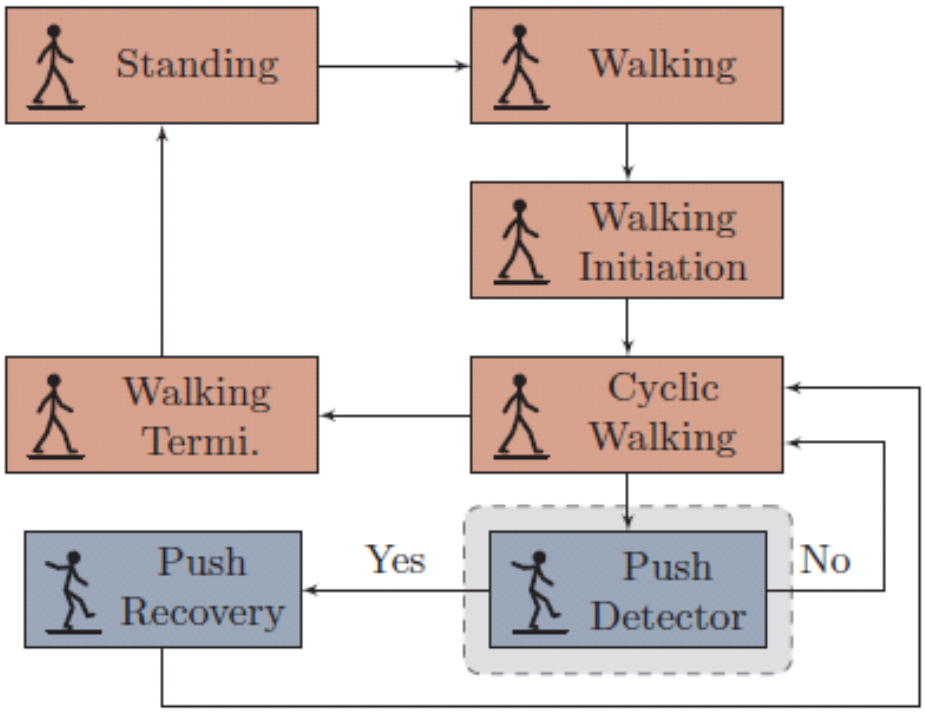
Support Surface Rotating at 0.6 Hz, +-2° Amplitude

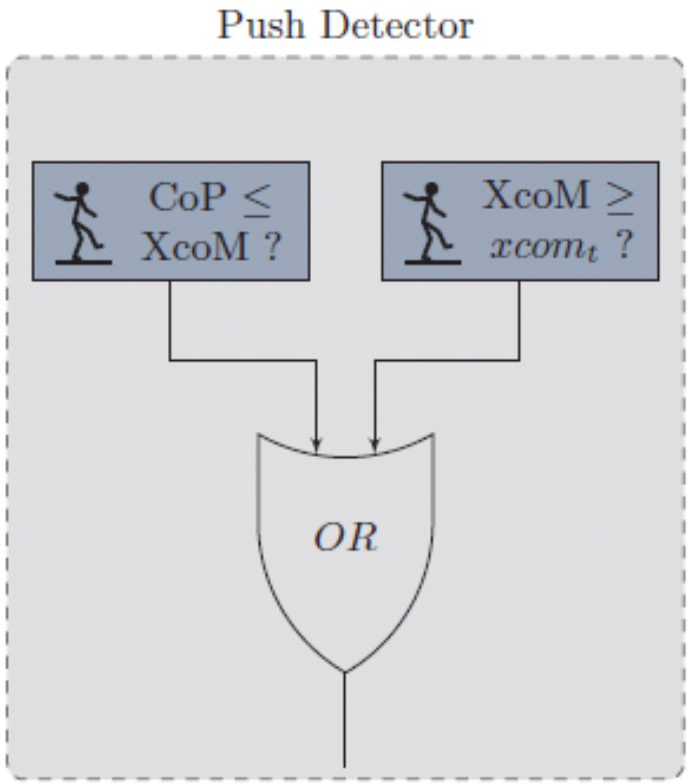
Support Surface Rotating at 0.6 Hz, +-6° Amplitude

Support Surface Rotating at 0.6 Hz, +-2° Amplitude, random offset

Strategies for Push Recovery while Walking

Push Recovery - Detection

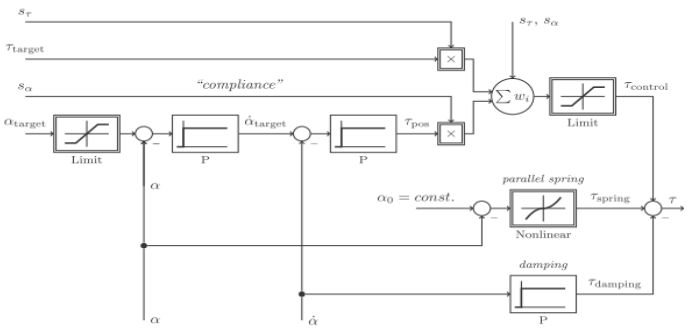




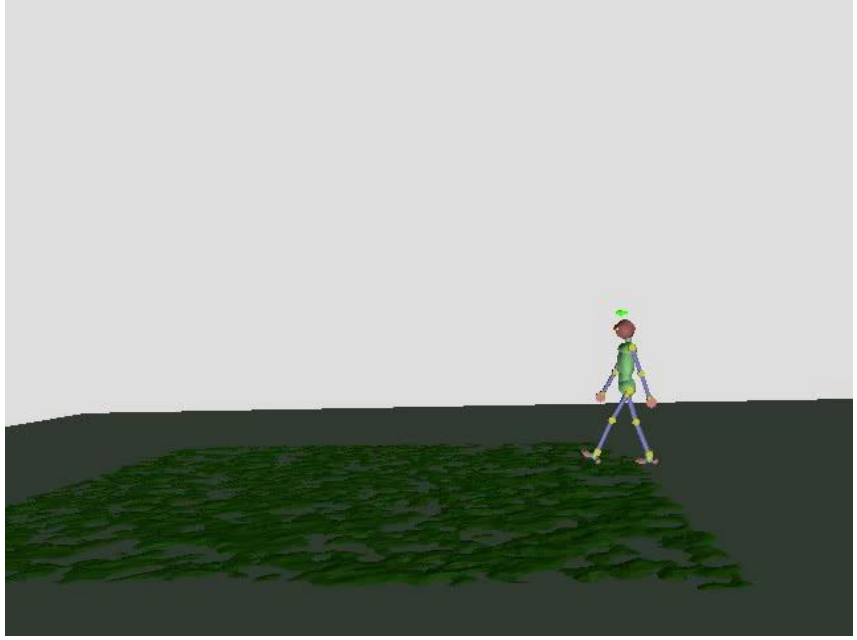
[Hof05, Hof08]

Push Recovery - Strategies

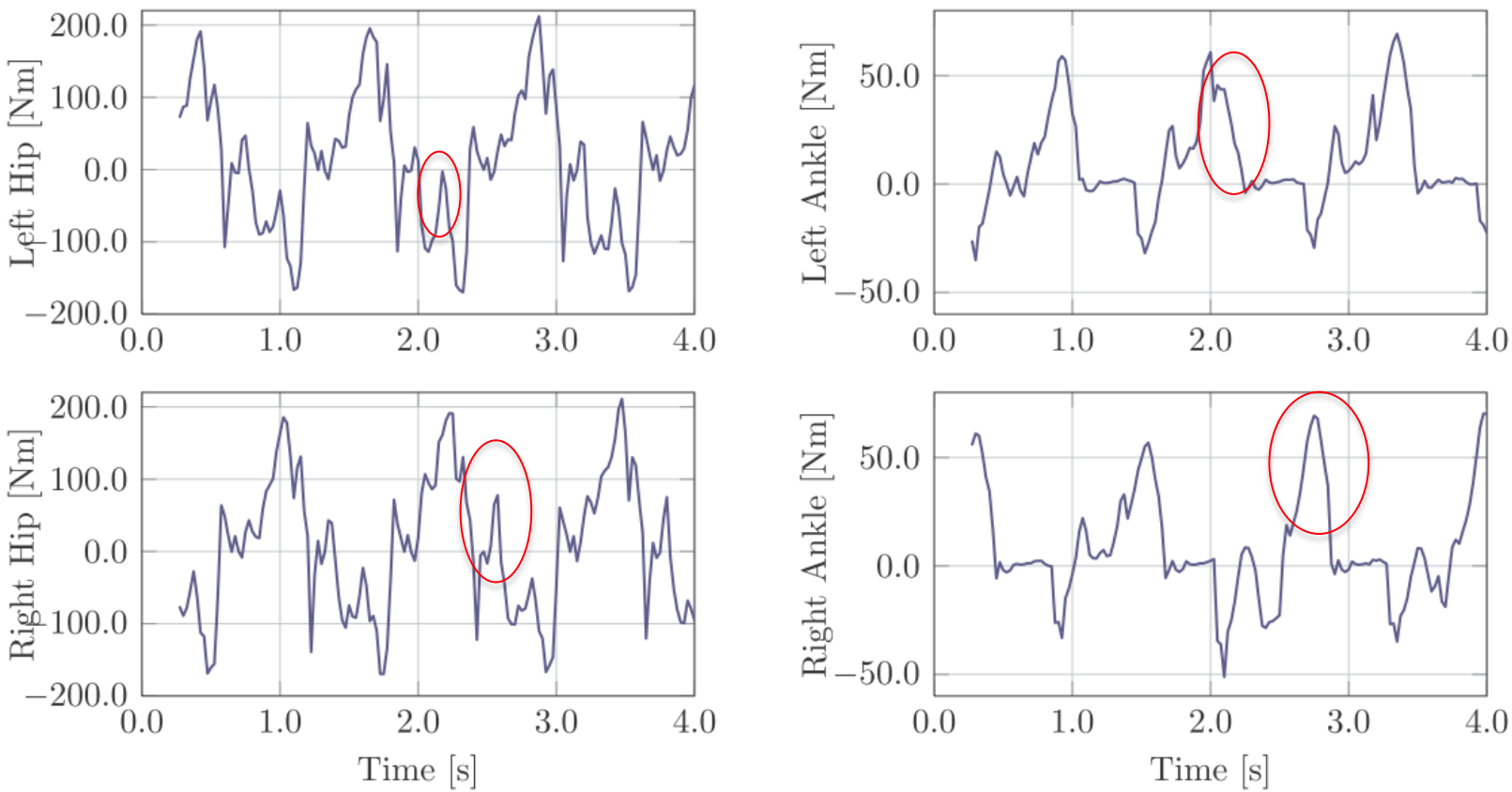
- Hip and Ankle Strategy
  - If push is detected when both legs in ground contact.
  - Additional torque on hip and ankle joint of the leg next to leave ground.
- Knee Strategy
  - If push is detected during swing phase or weight acceptance.
  - Stiffness and equilibrium point of knee joint are modulated.



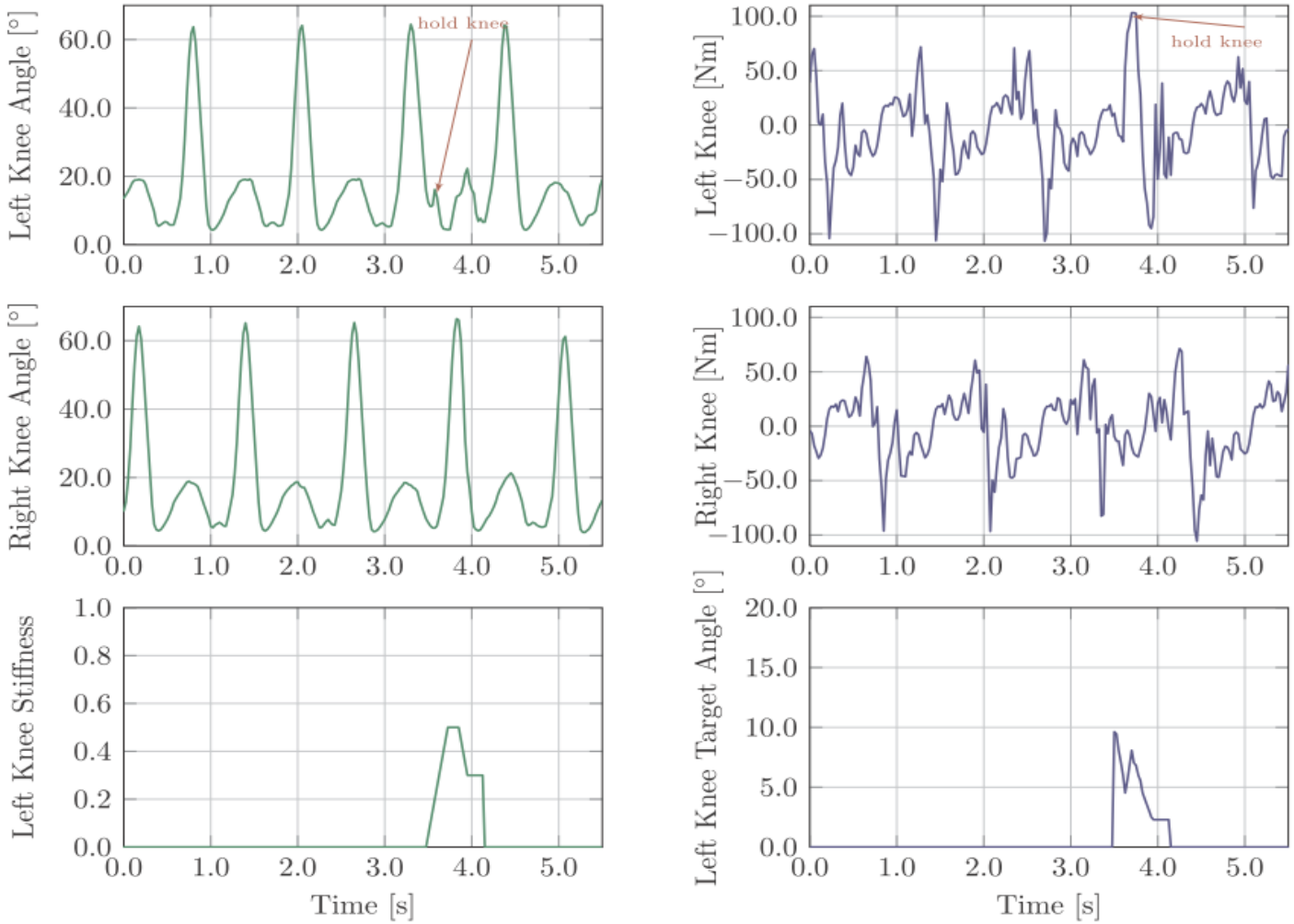
Push Recovery - Experiments



Push Recovery – Results Hip Ankle Strategy



Push Recovery – Results Knee Strategy



Conclusion

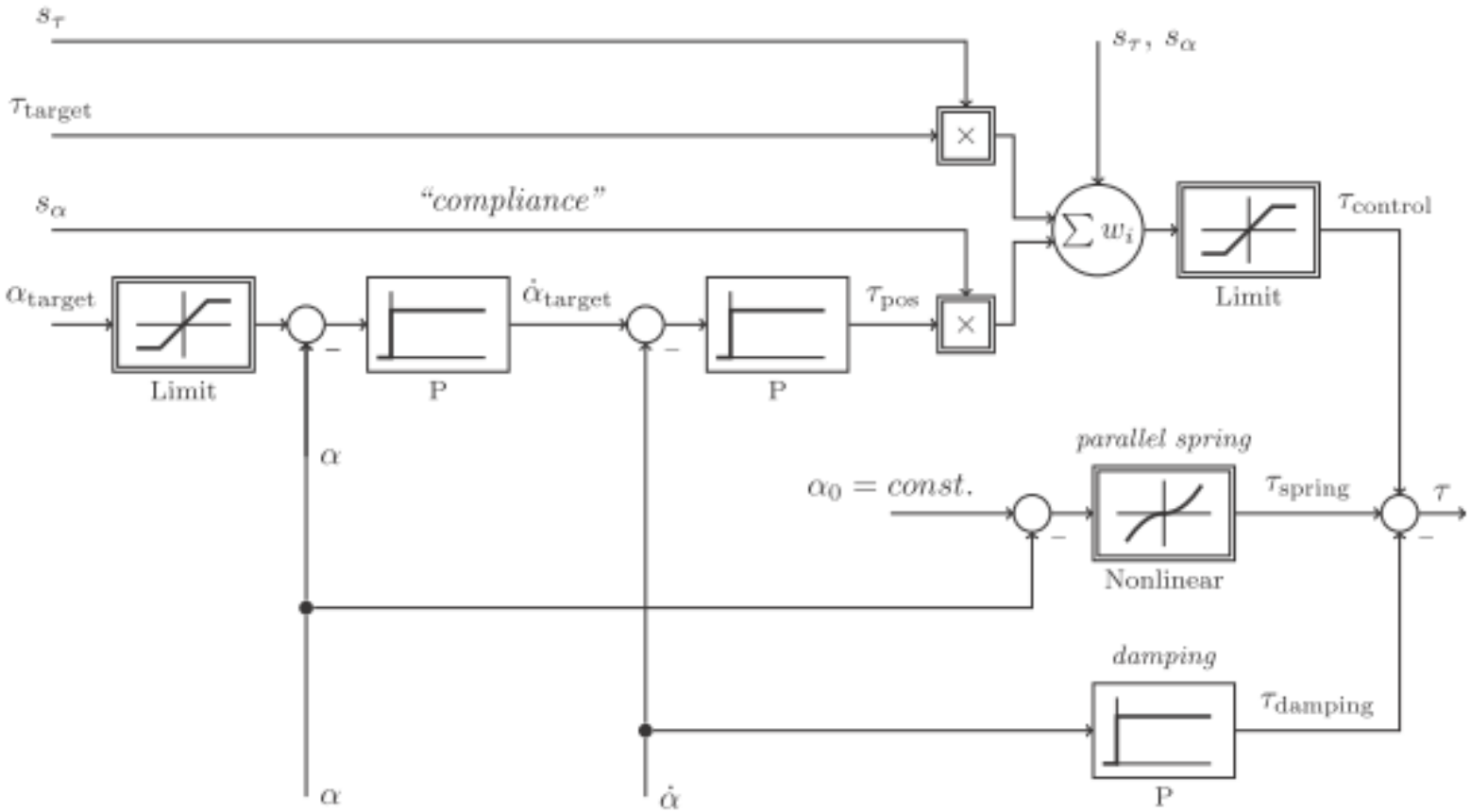
- In General:
  - Further mechanisms/principles identified in biology, neuroscience and biomechanics can be easily integrated.
  - Behavior network can be extended and optimized.
- DEC
  - Applied to one joint – extension to multiple joints?
- Push recovery
  - Only saggital disturbances – strategies for lateral pushes?

References

- [Luksch10] T. Luksch, “Human-like control of dynamically walking bipedal robots,” Ph.D. dissertation, University of Kaiserslautern, 2010.
- [Proetzsch10] M. Proetzsch, T. Luksch, and K. Berns, “Development of complex robotic systems using the behavior-based control architecture iB2C,” Robotics and Autonomous Systems, 2010.
- [Mergner10] T. Mergner, “A neurological view on reactive human stance control,” Annual Reviews in Control, vol. 34, no. 2, pp. 177 – 198, 2010.
- [Hof08] A. Hof, “The ”extrapolated center of mass” concept suggests a simple control of balance in walking,” Human Movement Science, vol. 27, no. 1, pp. 112–125, 2008.
- [Hof05] A. Hof, M. Gazendam, and W. Sinke, “The condition for dynamic stability,” Journal of Biomechanics, vol. 38, no. 1, pp. 1–8, 2005.

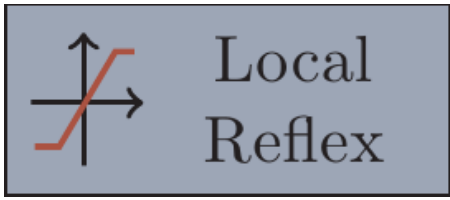
Thank you for your attention!

Joint Control Simulated Biped

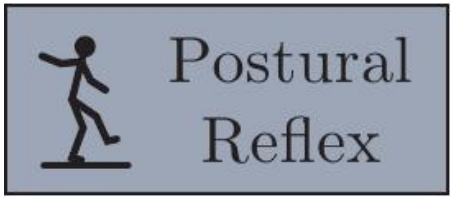


Reflex Controllers

- Local reflexes:
  - feedback mechanism
  - kinematic event-based triggering

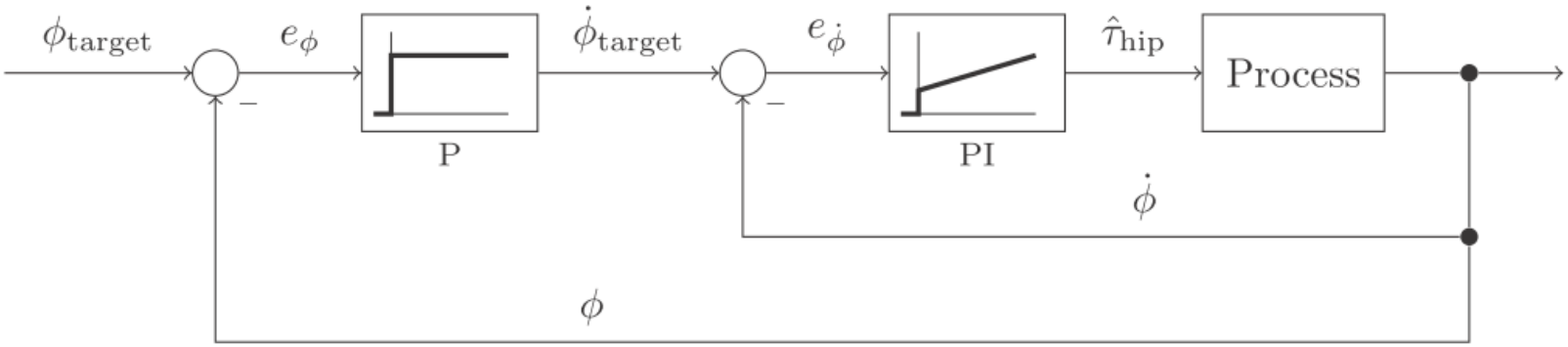


- Postural reflexes:
  - Supraspinal reflexes and more complex than local feedback
  - estimation of upper body orientation
  - calculation of CoM and XcoM
  - foot placement and velocity correction.



Postural Reflexes – Upright Trunk

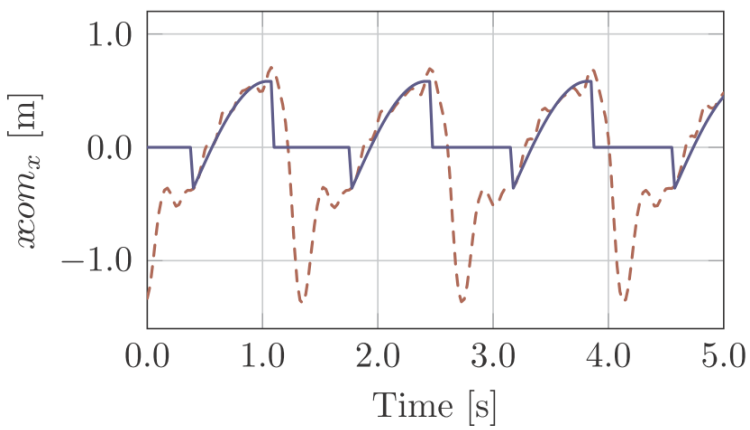
- Body stabilization in frontal plane
- Cascaded position-velocity controller
- Modulated by ground contact

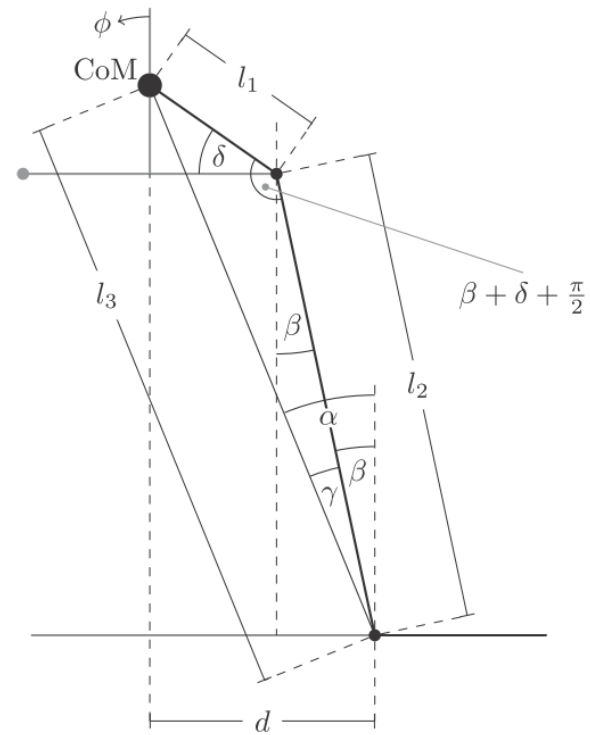


Postural Reflexes – Forward Velocity

- Calculates correction value to generate ankle torque about y-axis
- Trajectory of $xcom_x$ is compared to an approximation – sine wave:

$$xcom_{x,\text{target}} = v_{\text{target}} \left[xcom_{x,\text{start}} + (xcom_{x,\text{end}} - xcom_{x,\text{start}}) \sin\left(\frac{\pi}{2} t\right) \right]$$



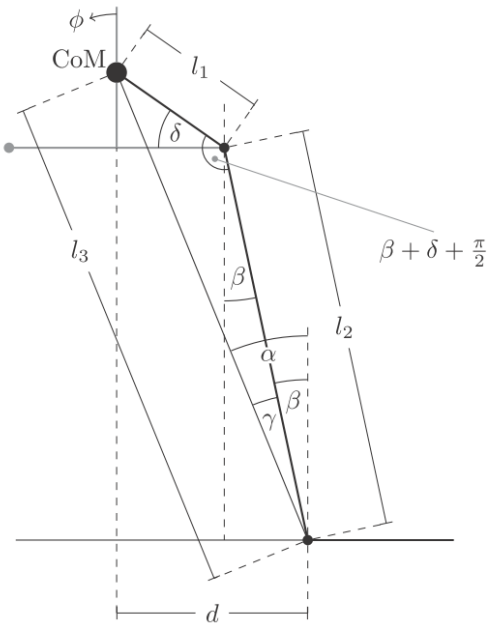


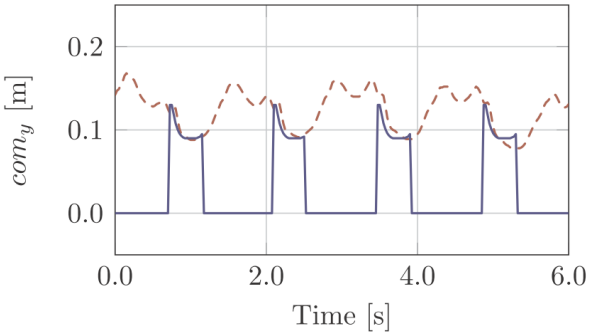
Postural Reflexes – Lateral Stability

- Trajectory of $xcom_y$ is compared to an approximation – fourth order polynomial:

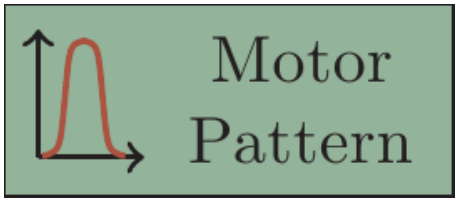
$$com_{y,\text{target}} = v_{\text{target}} \left[com_{y,\text{start}} + \left(com_{y,\text{end}} - com_{y,\text{start}} \right) \left(1 - (2t-1)^4 \right) \right]$$

- Lateral Balance Ankle
  - Calculates correction value to generate ankle torque about x-axis
- Lateral Foot Placement
  - Uses correction value to adapt hip angle during leg swing



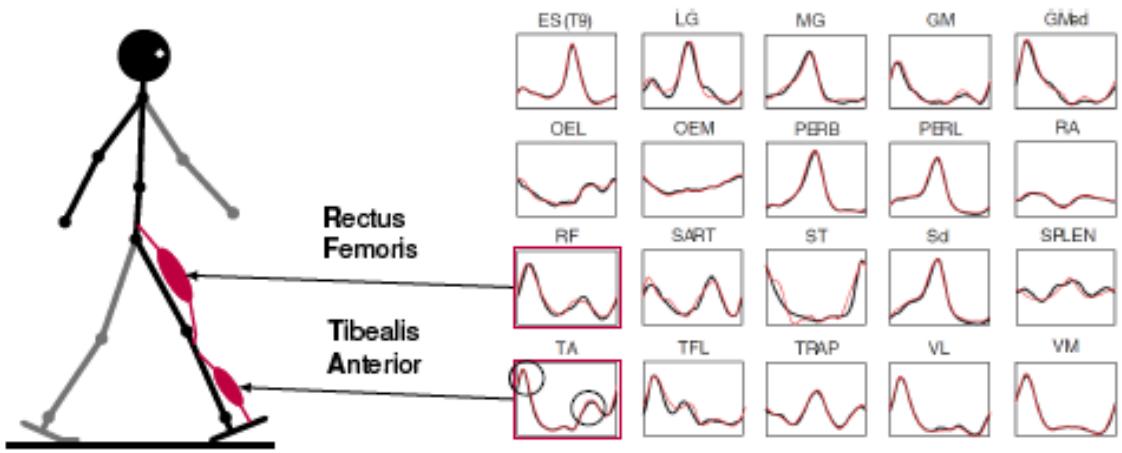


Motor Patterns

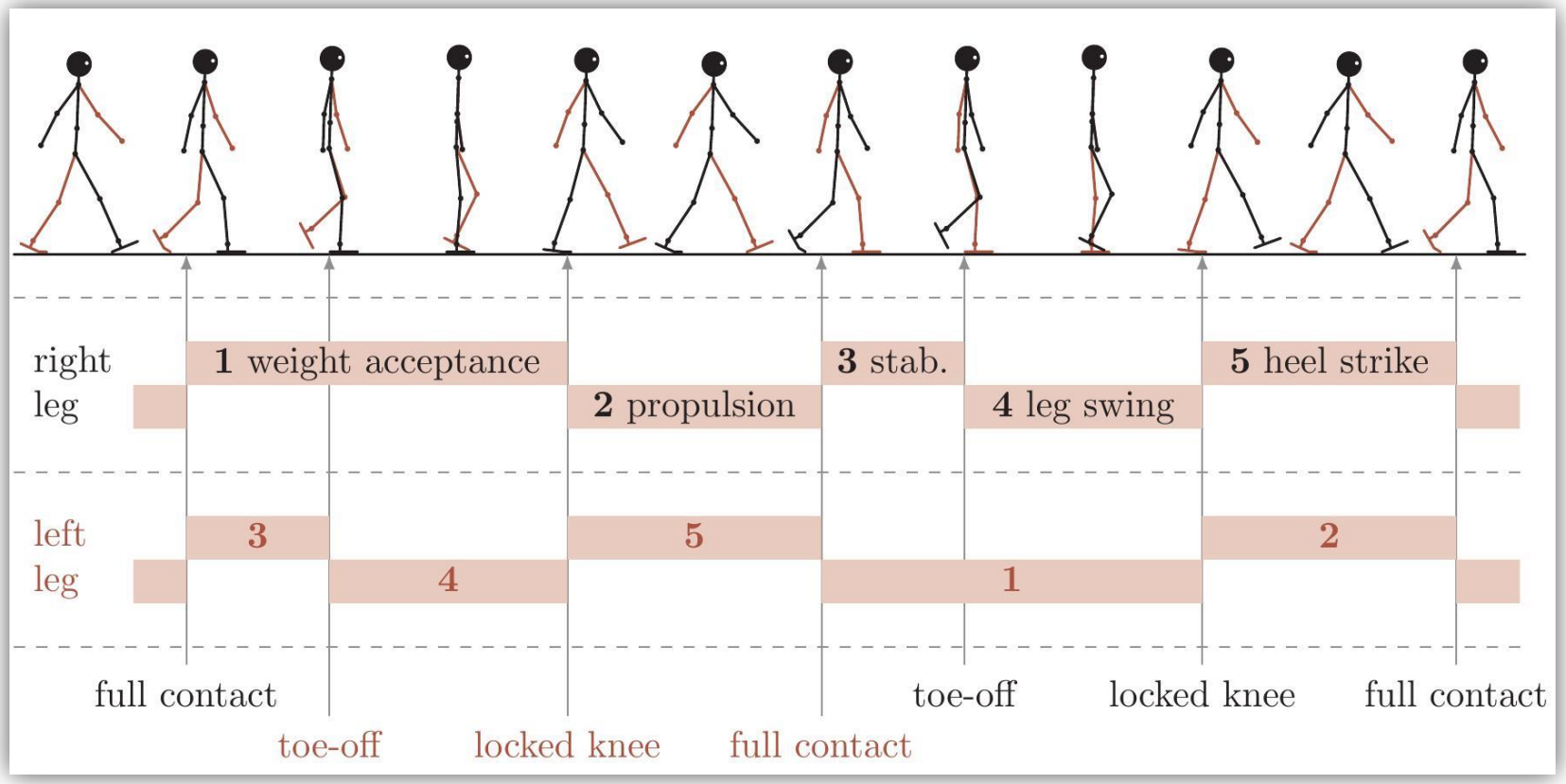


- feed-forward control
- analysis of muscle activities and kinetic data

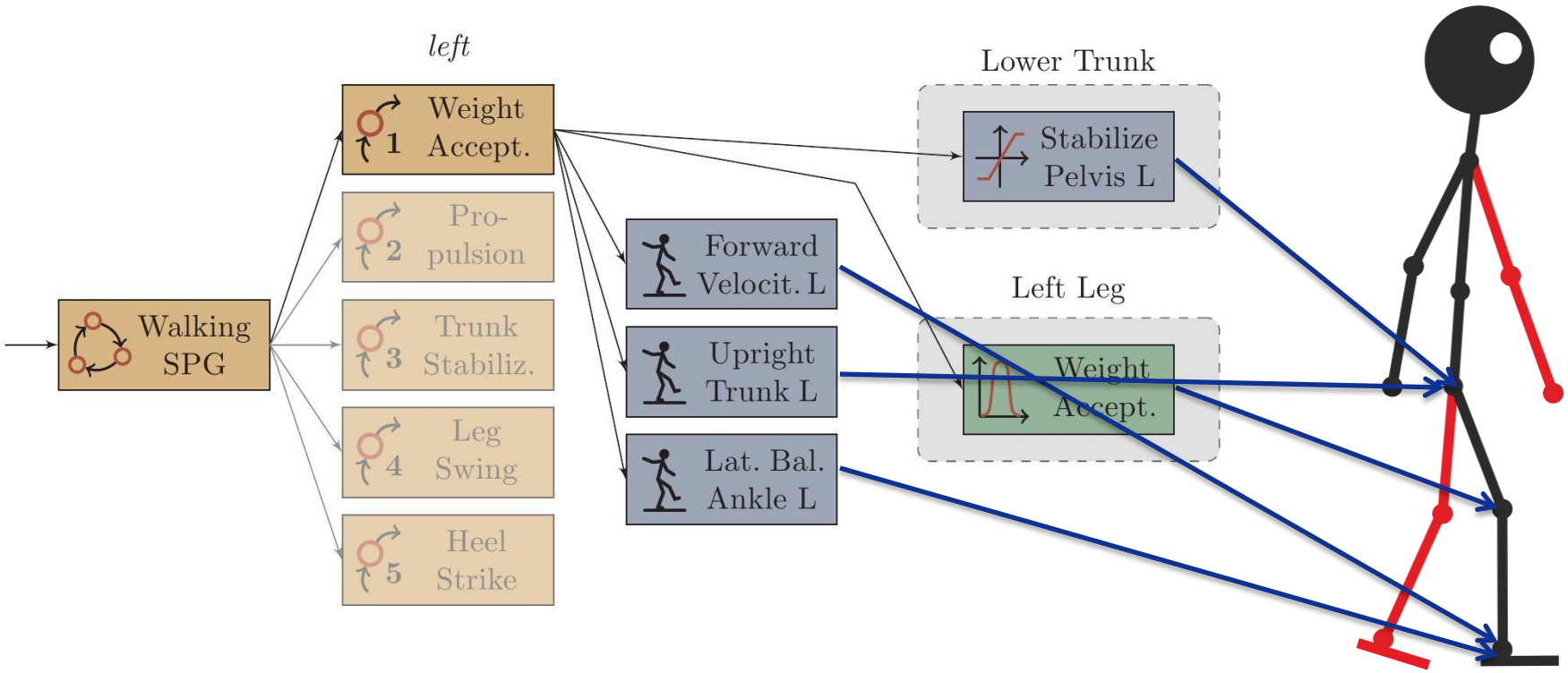
$$\hat{\tau} = \tau_{max} \begin{cases} \frac{1}{2} + \frac{1}{2}\sin\left(\pi\left(\frac{t}{T_1} - \frac{1}{2}\right)\right) & 0 \le t < T_1 \\ 1 & T_1 \le t < T_2 \\ \frac{1}{2} - \frac{1}{2}\sin\left(\pi\left(\frac{t - T_2}{T_3 - T_2} - \frac{1}{2}\right)\right) & T_2 \le t \le T_3 \end{cases}$$



Phases of Walking

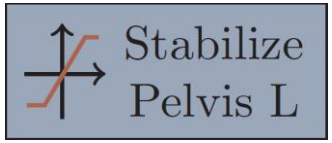


Walking Phase 1: Weight Acceptance

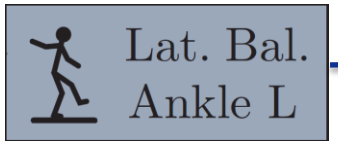


Walking Phase 1: Weight Acceptance

- Motor Pattern: to control knee joint to guarantee a smooth weight acceptance.

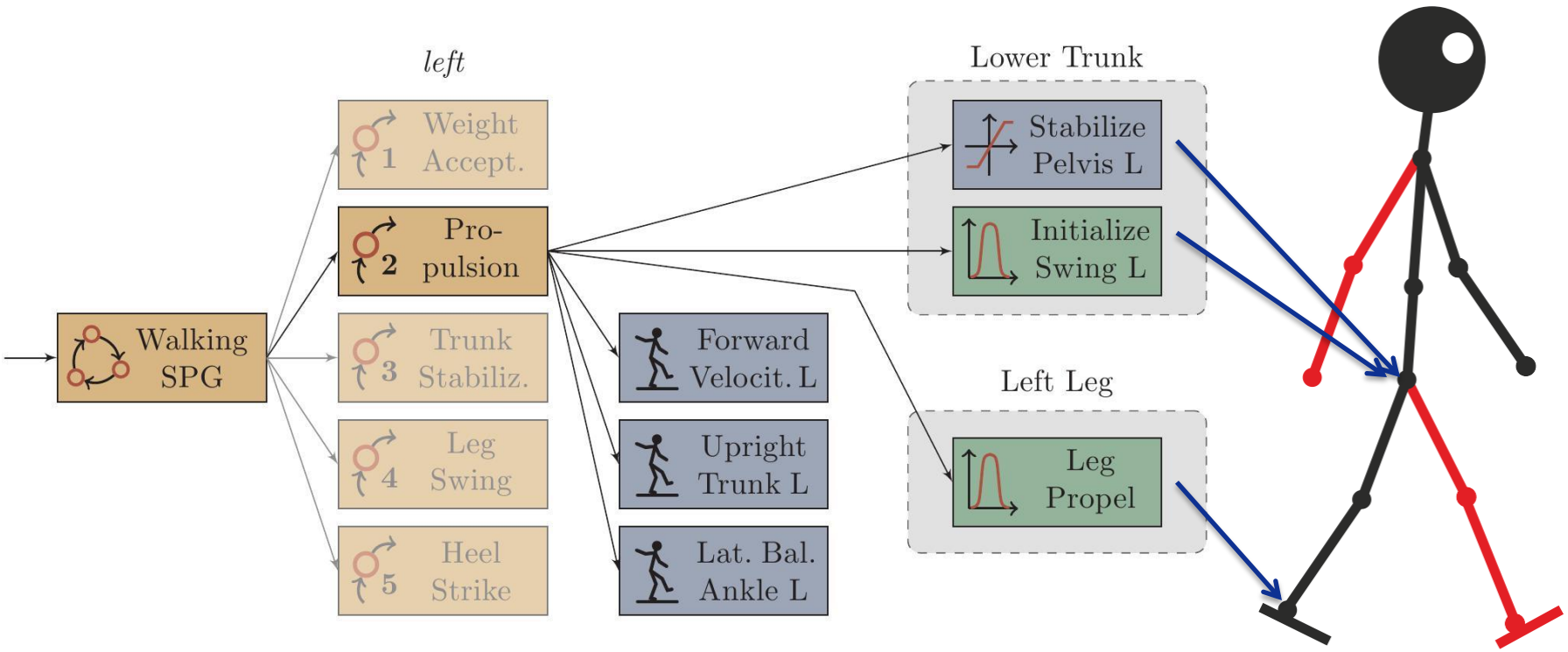


- Local Reflexes: to stabilize the pelvis about the x-axis.
- Other joints of upper trunk passively controlled.

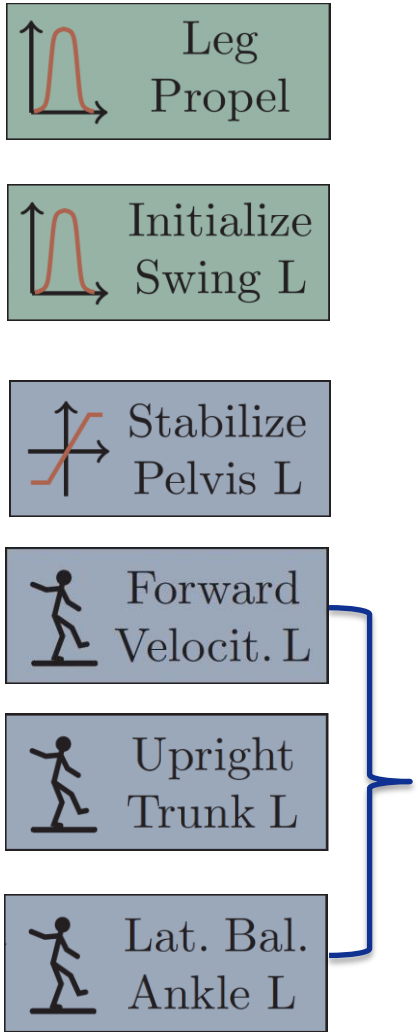


- Postural Reflexes: to aim for suitable forward velocity, posture of upper trunk and lateral stabilization

Walking Phase 2: Propulsion

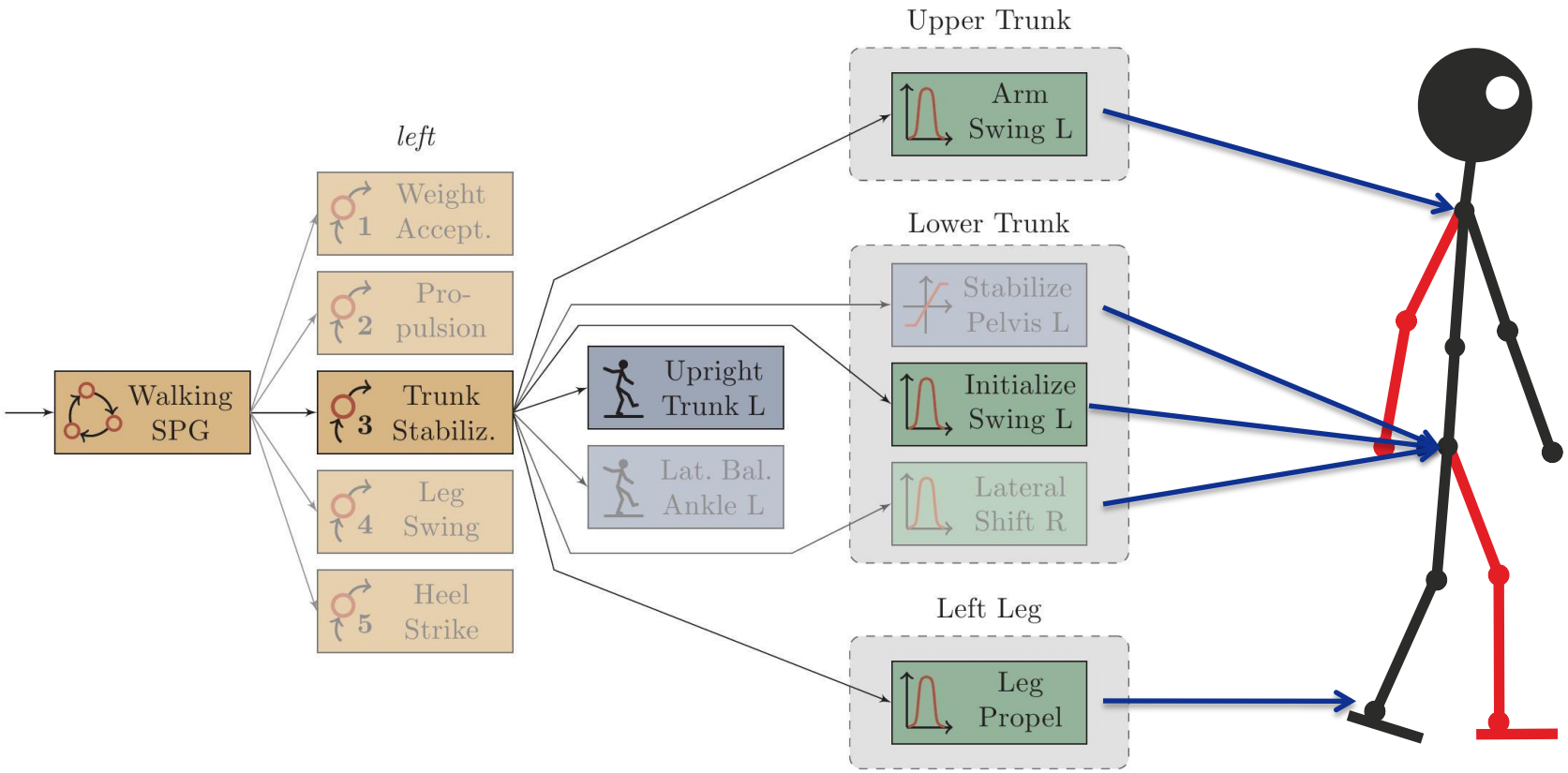


Walking Phase 2: Propulsion



- Motor Pattern: to create a plantarflexion of ankle.
- Motor Pattern: to start leg swing.
- Local Reflexes: to stabilize the pelvis.
- Postural Reflexes: to aim for suitable forward velocity, posture of upper trunk and lateral stabilization

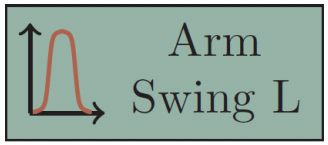
Walking Phase 3: Stabilization



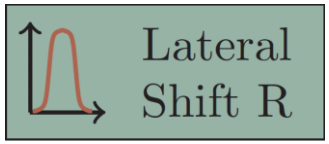
Walking Phase 3: Stabilization

- Motor Pattern: to push body forward.

- Motor Pattern: to continue leg swing.



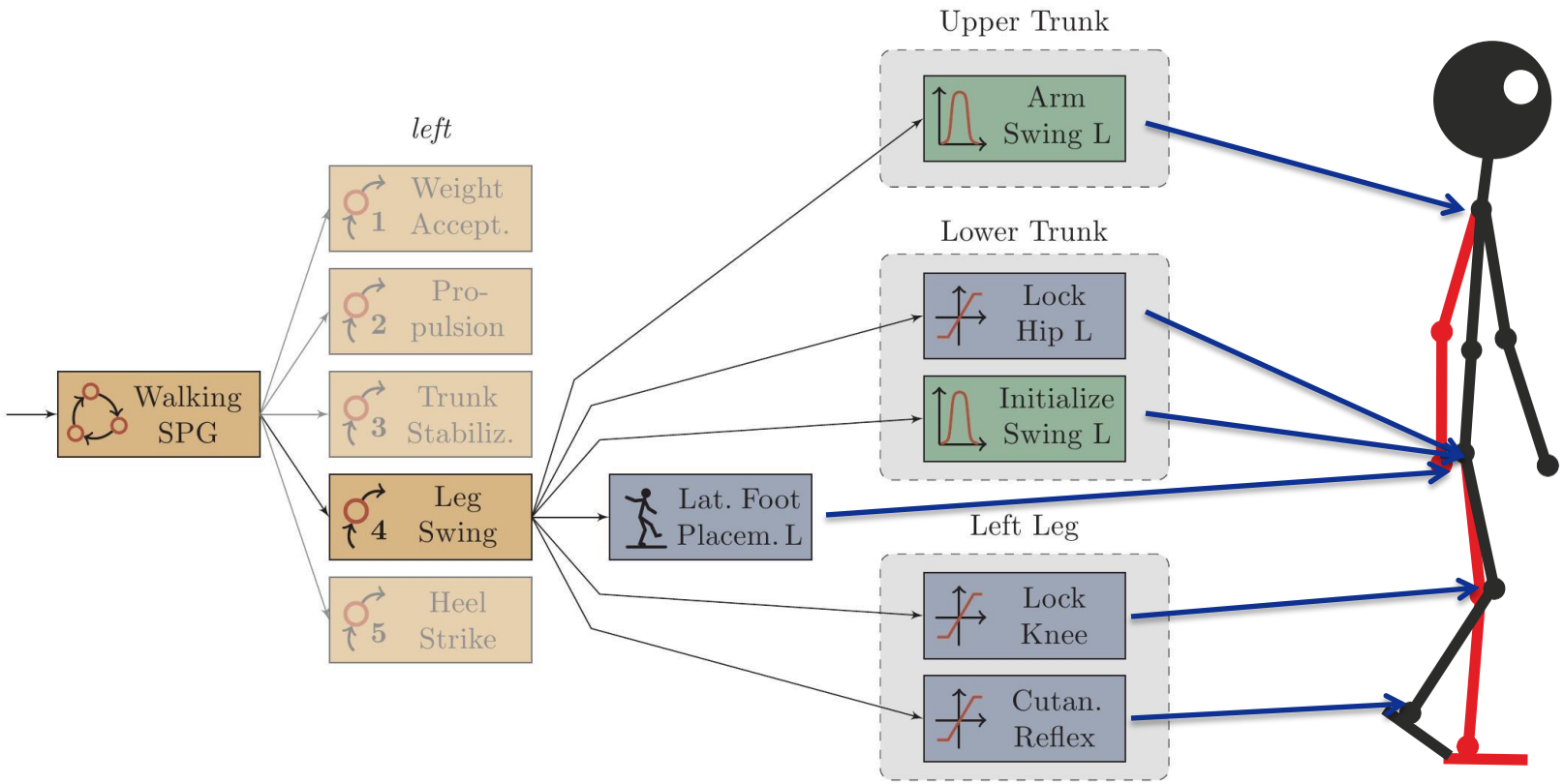
- Motor Pattern: to swing the arm.



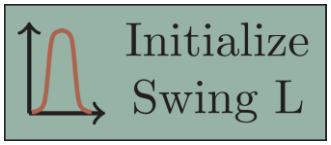
- Motor Pattern: to move the CoM to the stance leg.

- Postural Reflexes: to erect the upper trunk.

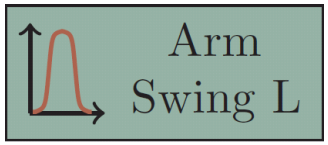
Walking Phase 4: Leg Swing



Walking Phase 4: Leg Swing

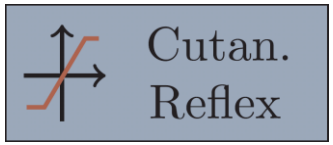


- Motor Pattern: to continue leg swing.



- Motor Pattern: to swing the arm.

- Local Reflexes: to stretch the knee joint.

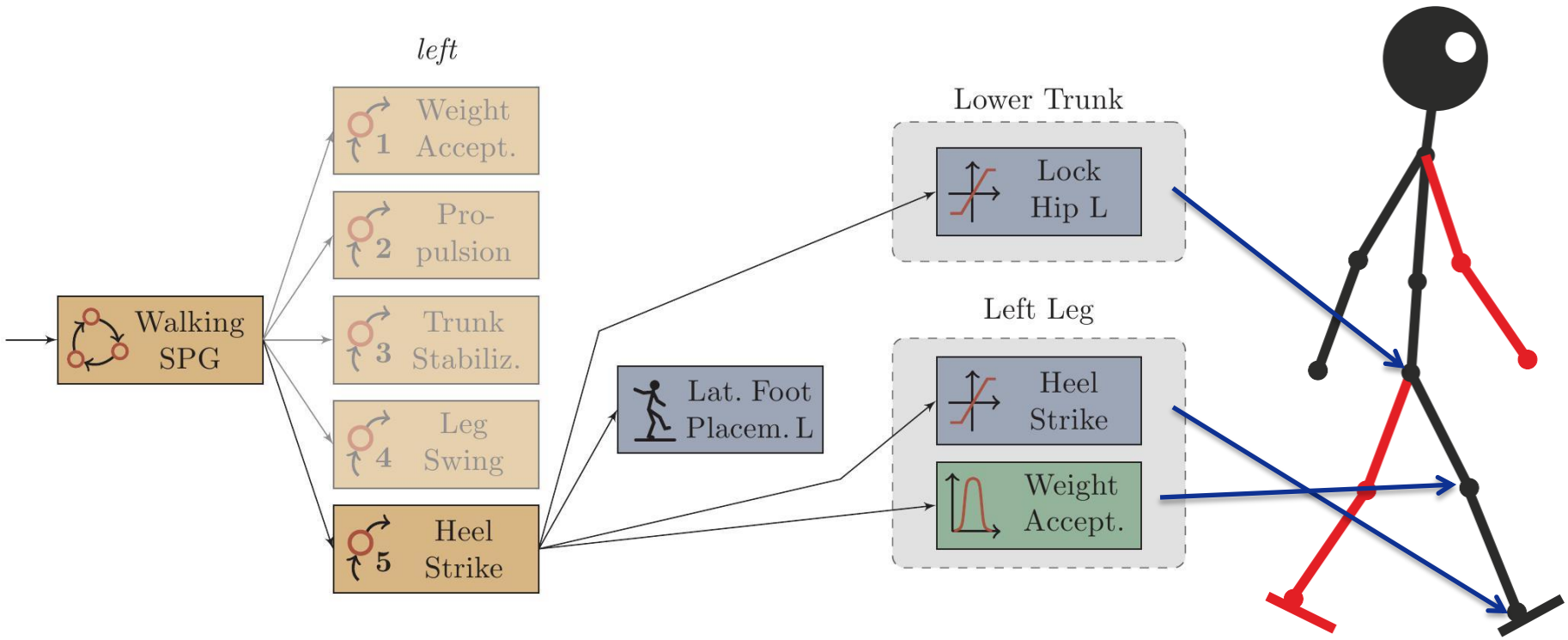


- Local Reflexes: to establish ground clearance.

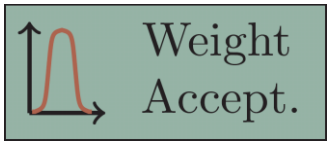
- Local Reflexes: to achieve a suitable angle of attack at heel strike.

- Postural Reflexes: to adapt hip angle during swing phase.

Walking Phase 5: Heel Strike



Walking Phase 5: Heel Strike



- Motor Pattern: to keep knee stiff.

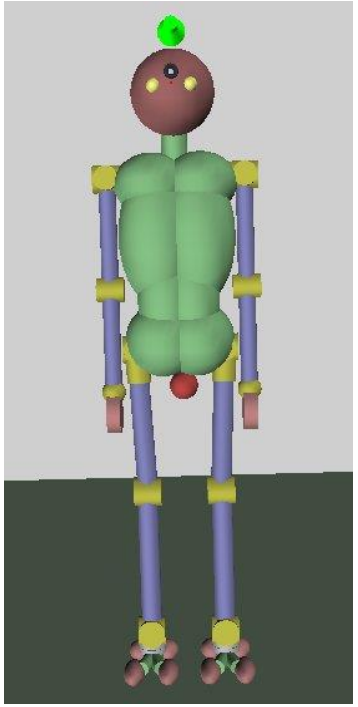
- Local Reflexes: to prevent hip from overswinging.

- Local Reflexes: to generate a damping torque to soften foot plantarflexion.

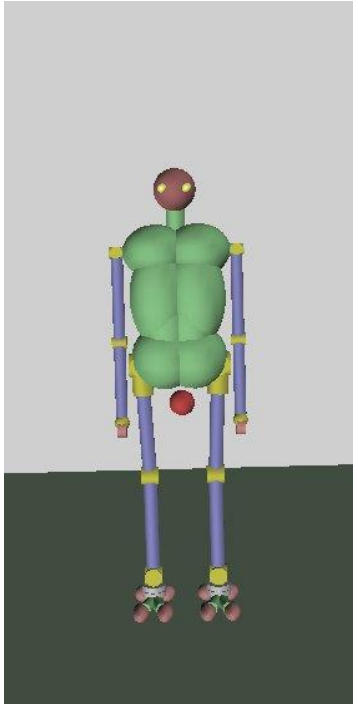
- Postural Reflexes: to adapt hip angle to land the foot suitably.

Scaling of Biped I

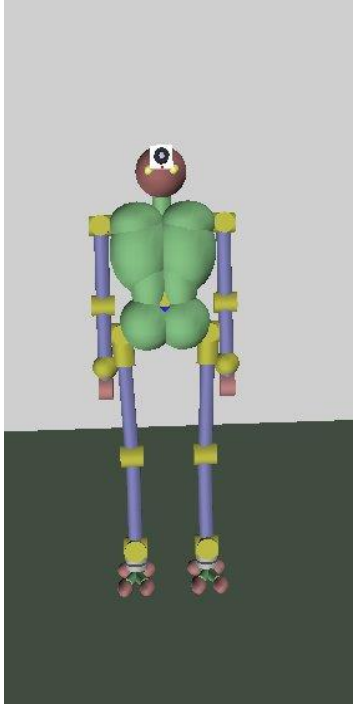
Size	1.8m	1.52m	1.26m
Weight	78kg	58kg	40kg
DoFs	21	21	21



Biped 1.8m



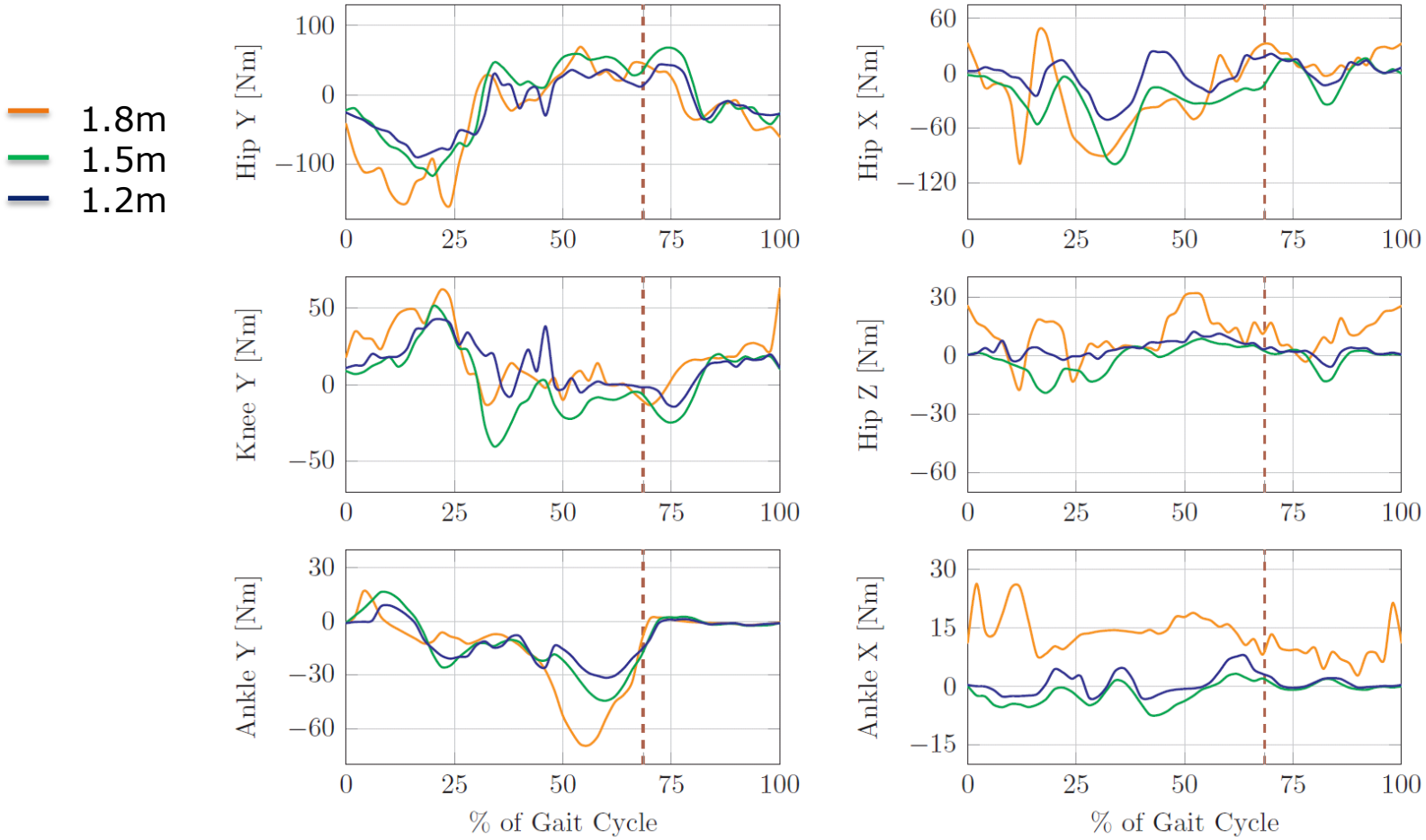
Biped 1.52m



Biped 1.26m

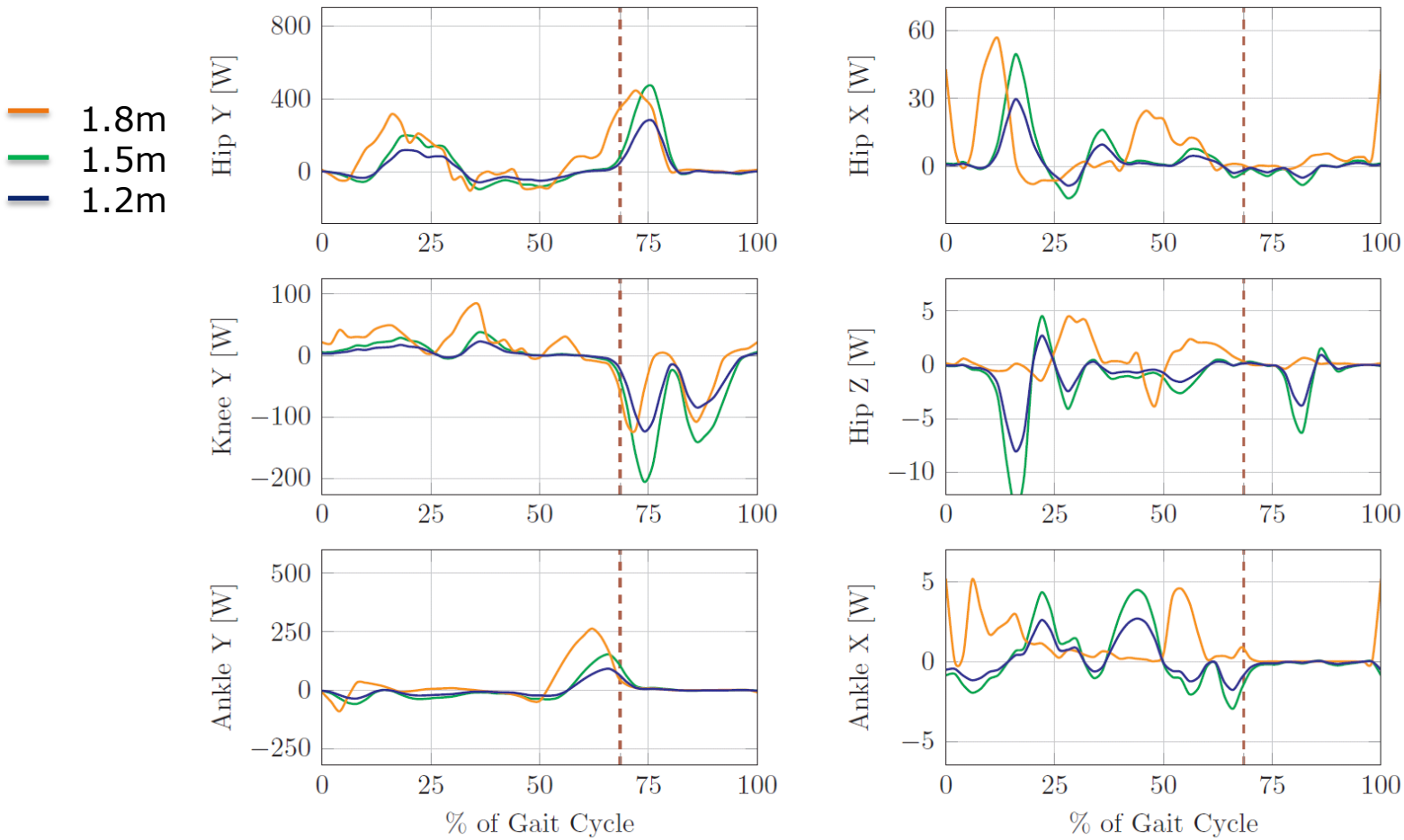
Scaling of Biped II

- Courses of torques during one gait cycle



Scaling of Biped III

- Courses of power during one gait cycle



Scaling of Biped IV

- Comparison of torques and power

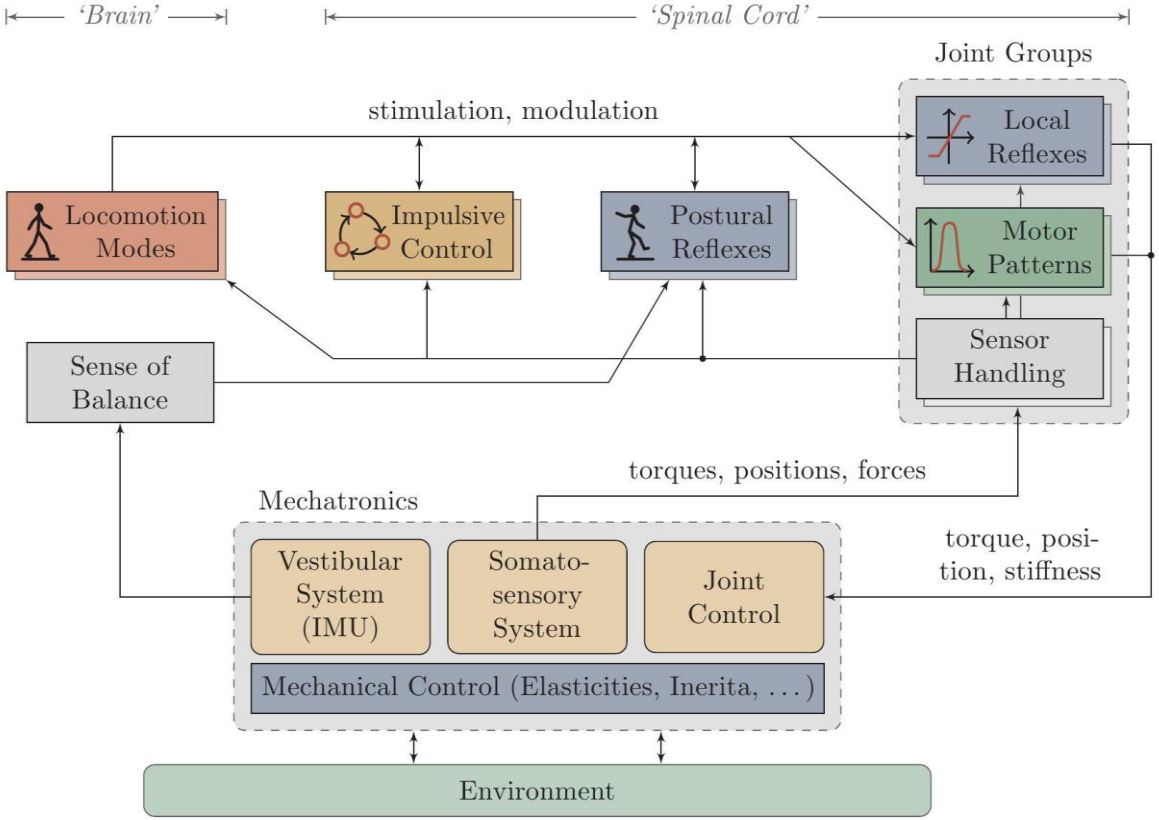
Joint	Peak Torque [Nm]			Maximum Power [W]		
	1.2m	1.5m	1.8m	1.2m	1.5m	1.8m
Spine Y	55.0	66.8	111.1	11.6	19.7	20.3
Hip X	50.7	99.3	95.4	29.7	29.5	28.8
Hip Y	89.5	116.8	174.3	279.3	307.8	382.9
Hip Z	12.1	19.2	21.9	8.0	8.3	3.1
Knee Y	42.6	51.2	81.6	60.1	63.4	66.6
Ankle X	7.9	7.3	8.7	1.8	1.9	1.7
Ankle Y	31.5	44.2	61.4	70.7	153.1	230.9

Conclusion of Scaling Biped

- Most existing control units suitable for different sizes of biped
- Joints in frontal plane critical for lateral stability
- Less robustness of stability requiring more control efforts
- More flexible learning controller required

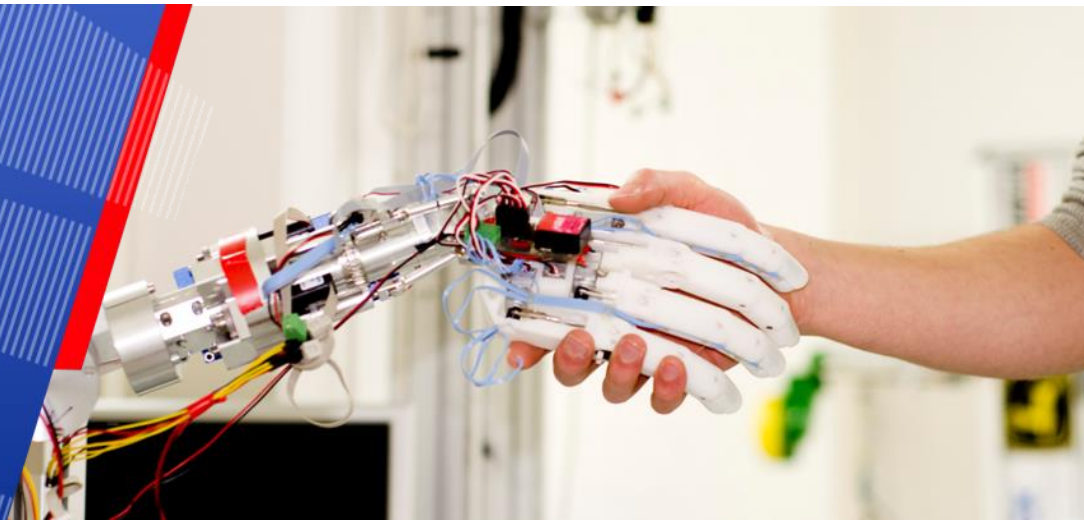
Integration of Impulsive Control

- Feed-forward control units replaced by impulsive control
- Convenient for learning control
- Combination of time- and event-based control



Thank you for your attention!

Introduction of iB2C, MCA2 and Finroc



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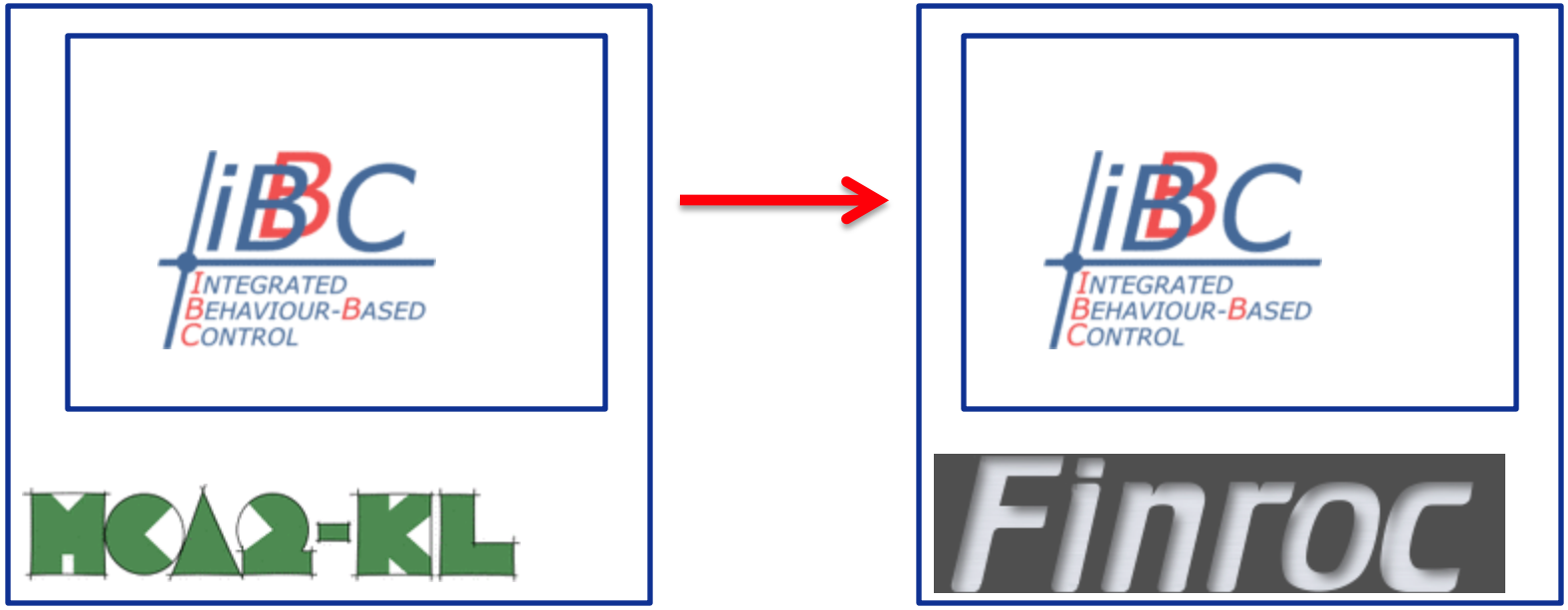
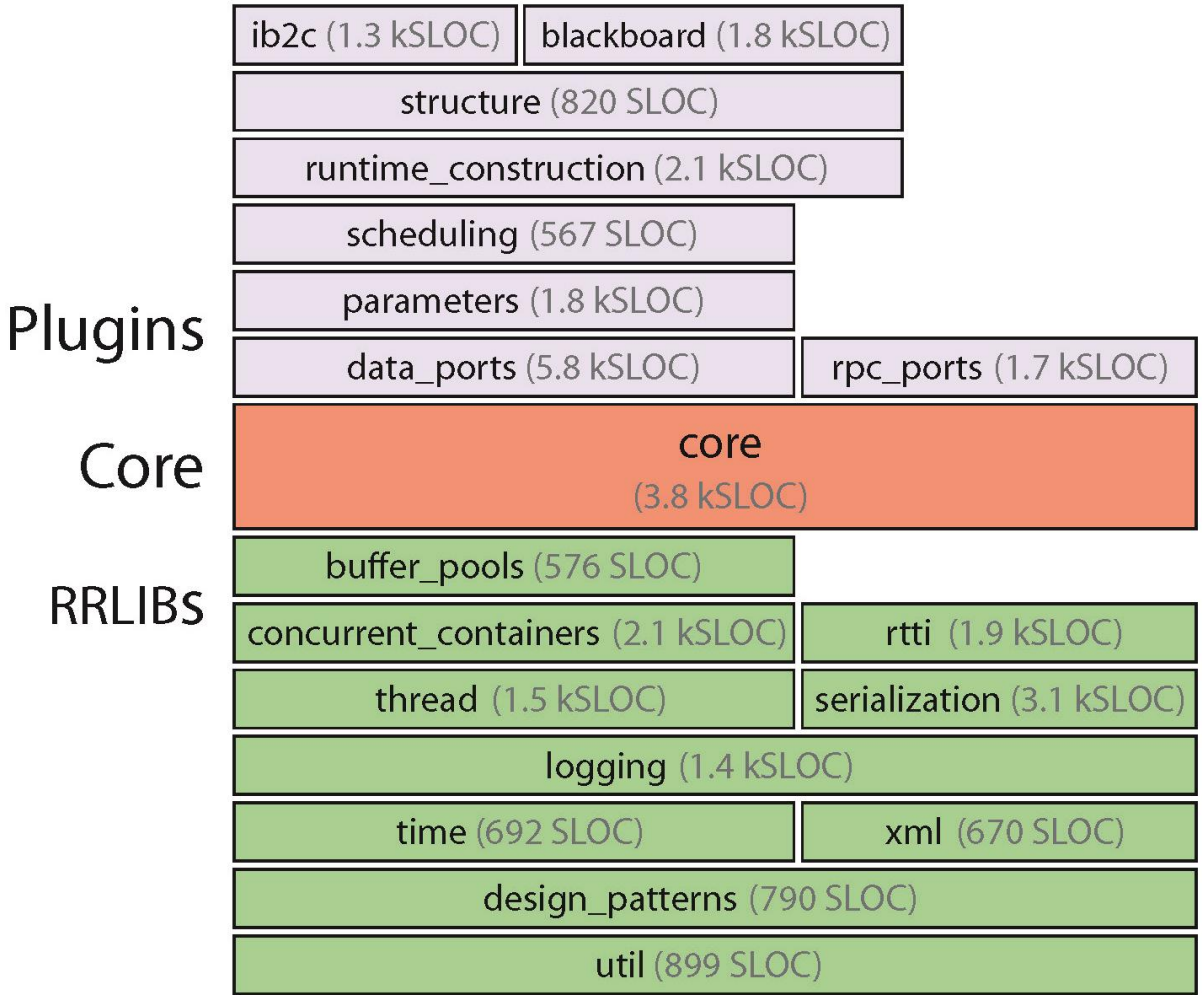
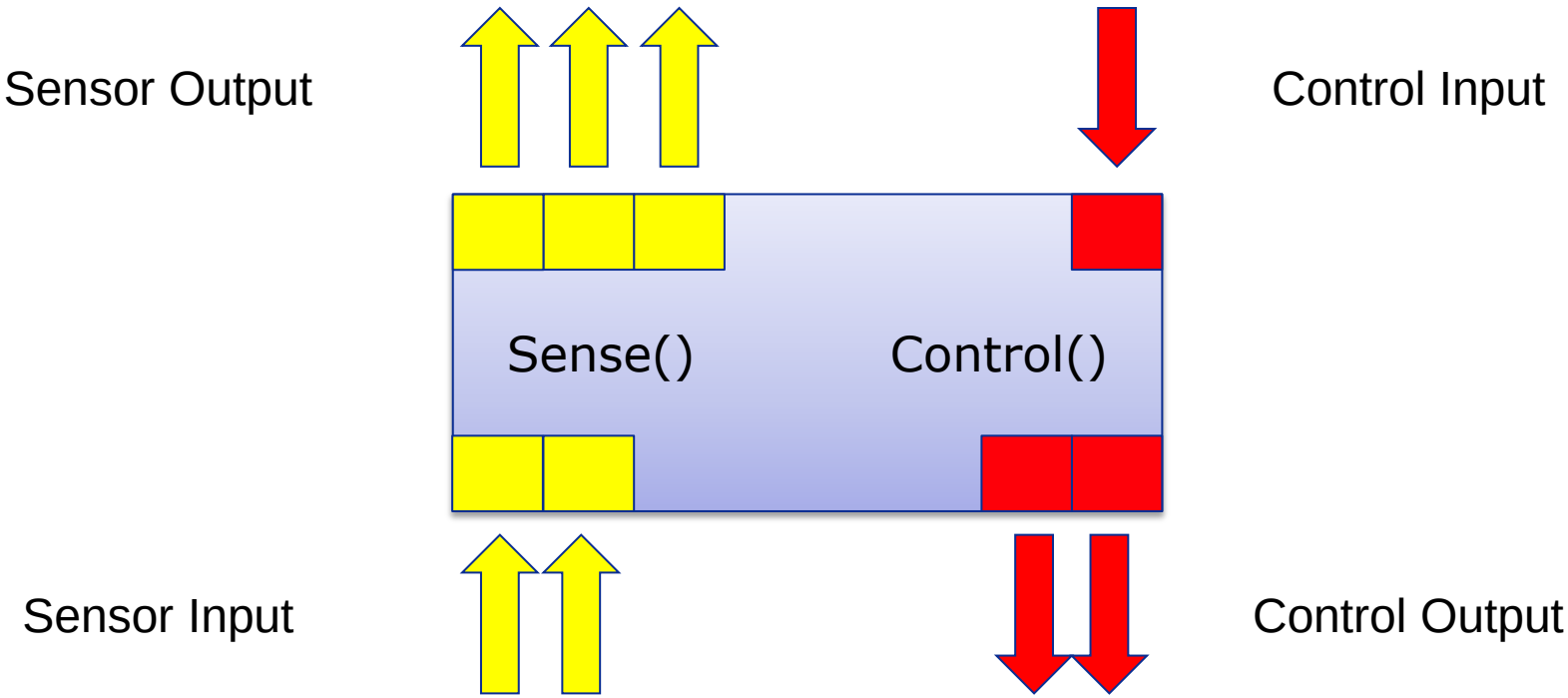
Framework


iBBC
INTEGRATED
BEHAVIOUR-BASED
CONTROL
MCA2-KL
iBBC
INTEGRATED
BEHAVIOUR-BASED
CONTROL
Finroc

Finroc Structure

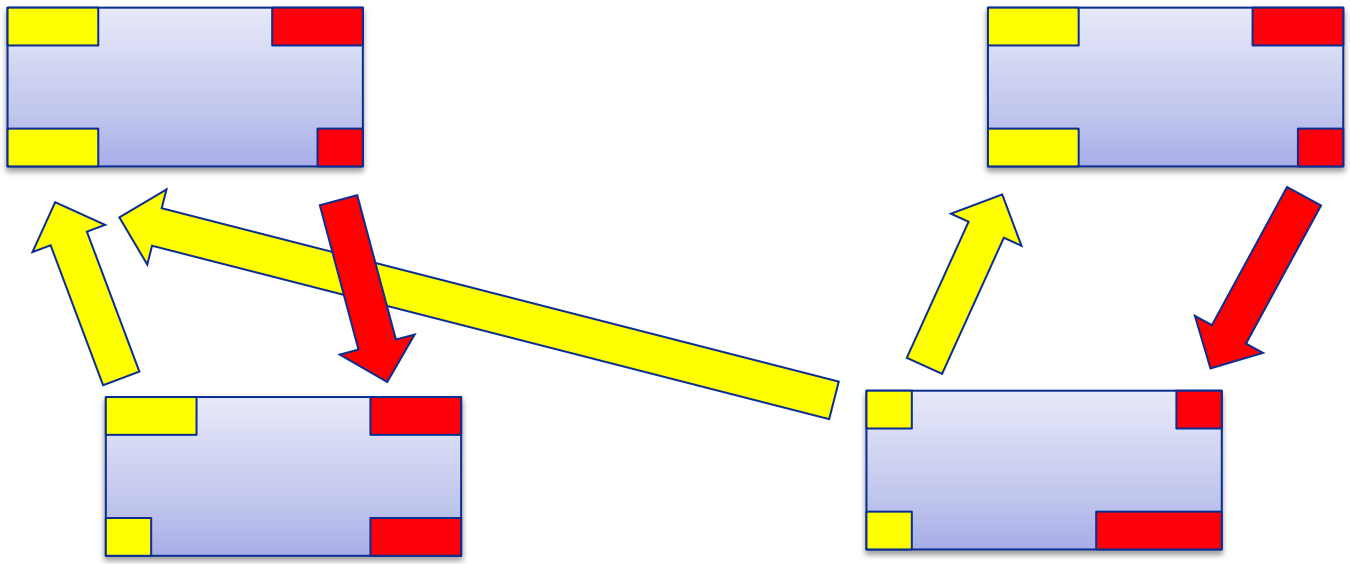


Basic Sense/Control Module



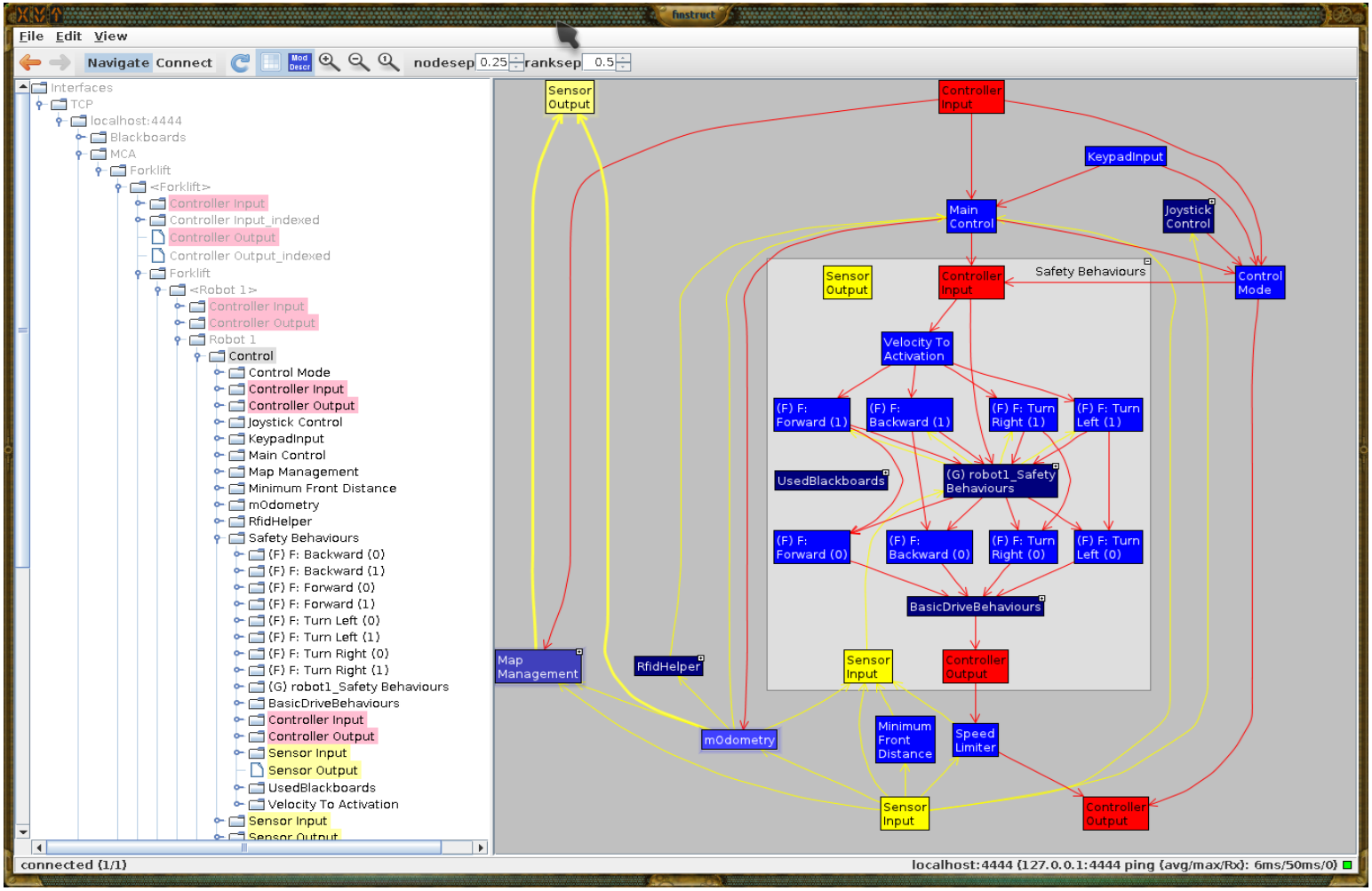
- Modules have inputs and outputs called Ports
- Ports can be any type (serializable)

Data Flow Interconnection



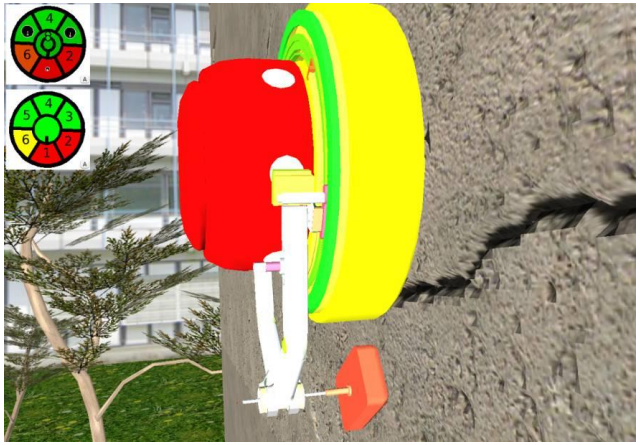
- 2 half-cycles: Sense() and Control()
- 1 source to many targets, at most one source per target
- “Directionless” modules available

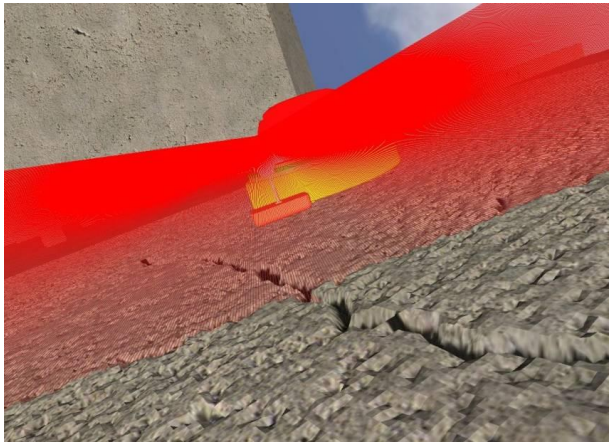
Finstruct Example



Simulation: SimVis3D

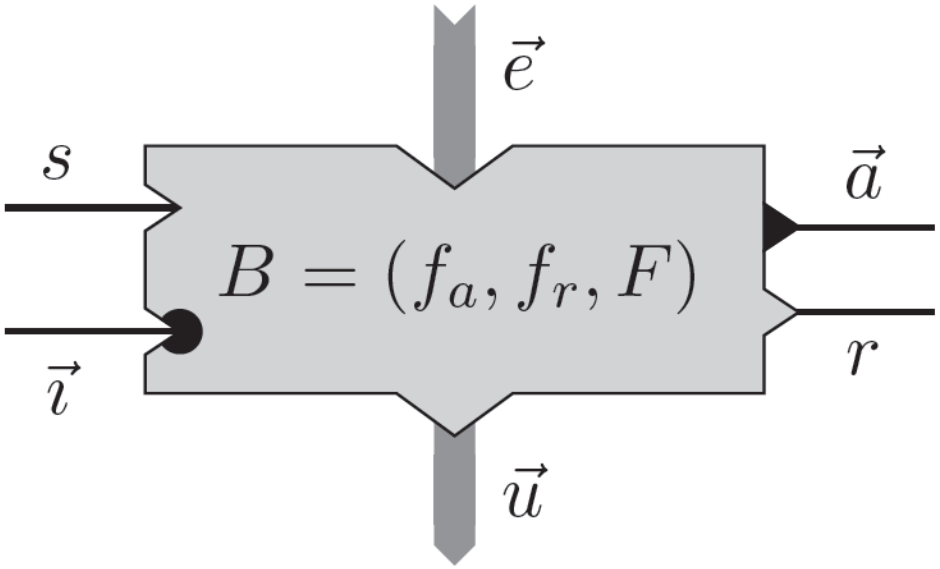
- All robots have simulation counterpart
- Identical interface for hardware abstraction and simulation
  → control program does not know if on real machine
- Finroc modules allow very high level of abstraction
- Simulation of pressures, engine currents, sensor noise





Integrated Behavior-based Control IB²C

- Input vector $\vec{e}$, output vector $\vec{u}$
- Stimulation s, inhibition vector $\vec{\imath}$
- Activity vector $\vec{a}$, target rating r
- Transfer function $\vec{u} = F(\vec{e}, \imath)$



Interaction

- Follow object & Avoid collision
- "Turn to object"
  - stimulated by "Follow object"
  - inhibited by "Avoid collision"
- Fusion: Weighted average