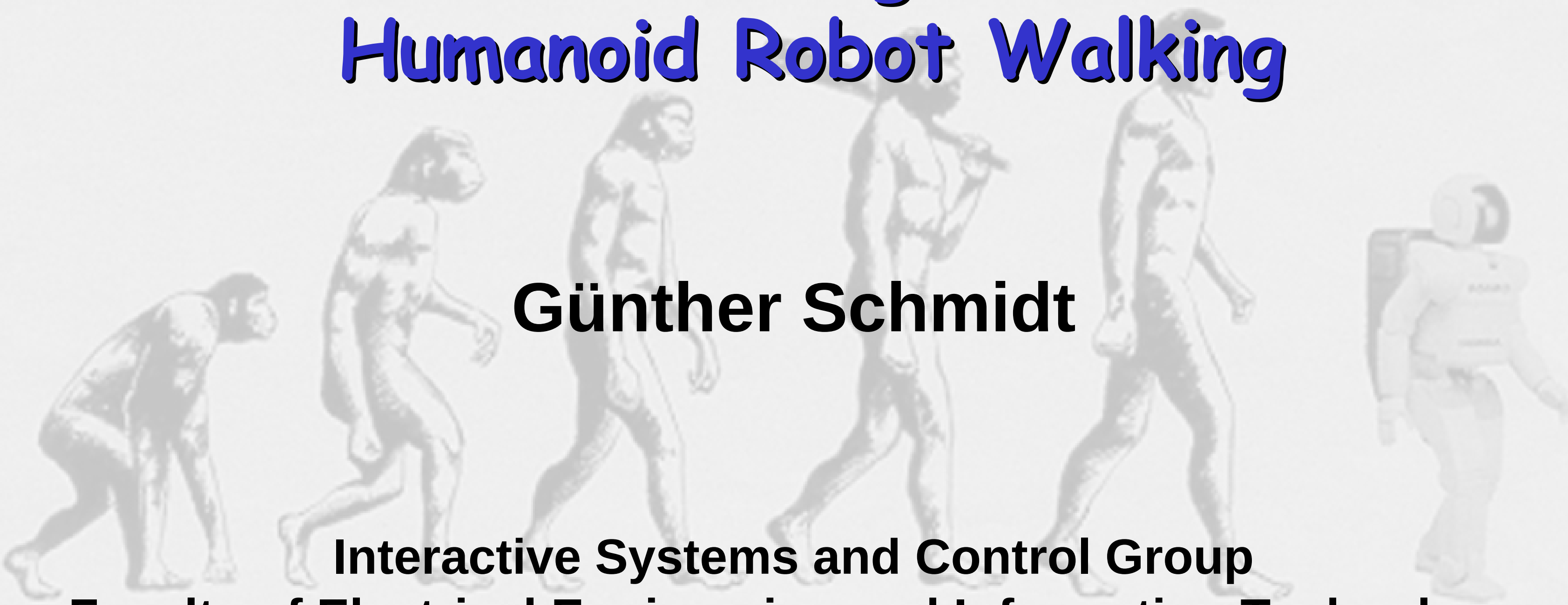
Artificial Cognitive Control Functionalities in Vision-guided Humanoid Robot Walking



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ECC'07, Semi-Plenary Lecture
Island of Kos, Greece, 4 July 2007

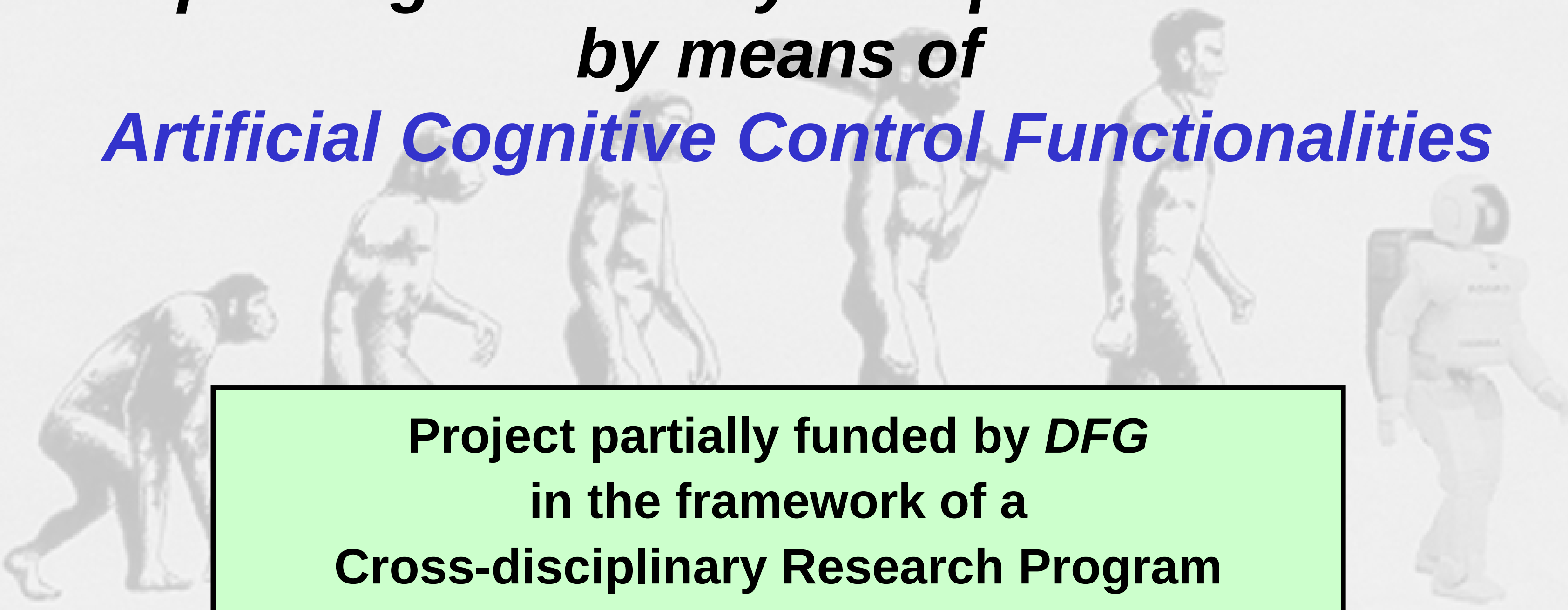
Abstract

The integration of basic cognitive functionalities into the operation of real-time, closed-loop systems seems to be one of the trends in control. Potential applications are found in vehicle and defence systems or robotics and mechatronics. With respect to biological models we distinguish perceptive, mental und executive cognitive functionalities. There exists also a close relationship between cognition and notions such as intelligence und autonomy.
Based on recent results from theoretical and experimental research in the field of intelligent humanoid robot walking this talk will demonstrate how some degree of locomotion autonomy can be achieved on the basis of artificial cognitive functionalities, such as step sequence planning and step adaptation by use of a walking primitive database, task-dependent visual perception and gaze control, as well as object classification and decision making.

HONDA Asimo: Even the experts may fail . . . .

Motivation

Improving Autonomy of Biped Locomotion
by means of
Artificial Cognitive Control Functionalities



Project partially funded by *DFG*
in the framework of a
Cross-disciplinary Research Program
"Autonomous Walking
in Robotic and Biological Systems"

Basis of Locomotion Autonomy in Humans and Robots ?

- **Cognitive Functionalities,**

"orchestration of perceptional and locomotion behaviours"

Related Notions

Cognitive functionalities

receptive: seeing, feeling, hearing, ...
mental: analysing, planning, learning, ...
executive: plan execution, attention, gaze, ...

Intelligence

Interplay of *(i) sensory-motor (cognitive) processes, (ii) body, (iii) environment*

Autonomy

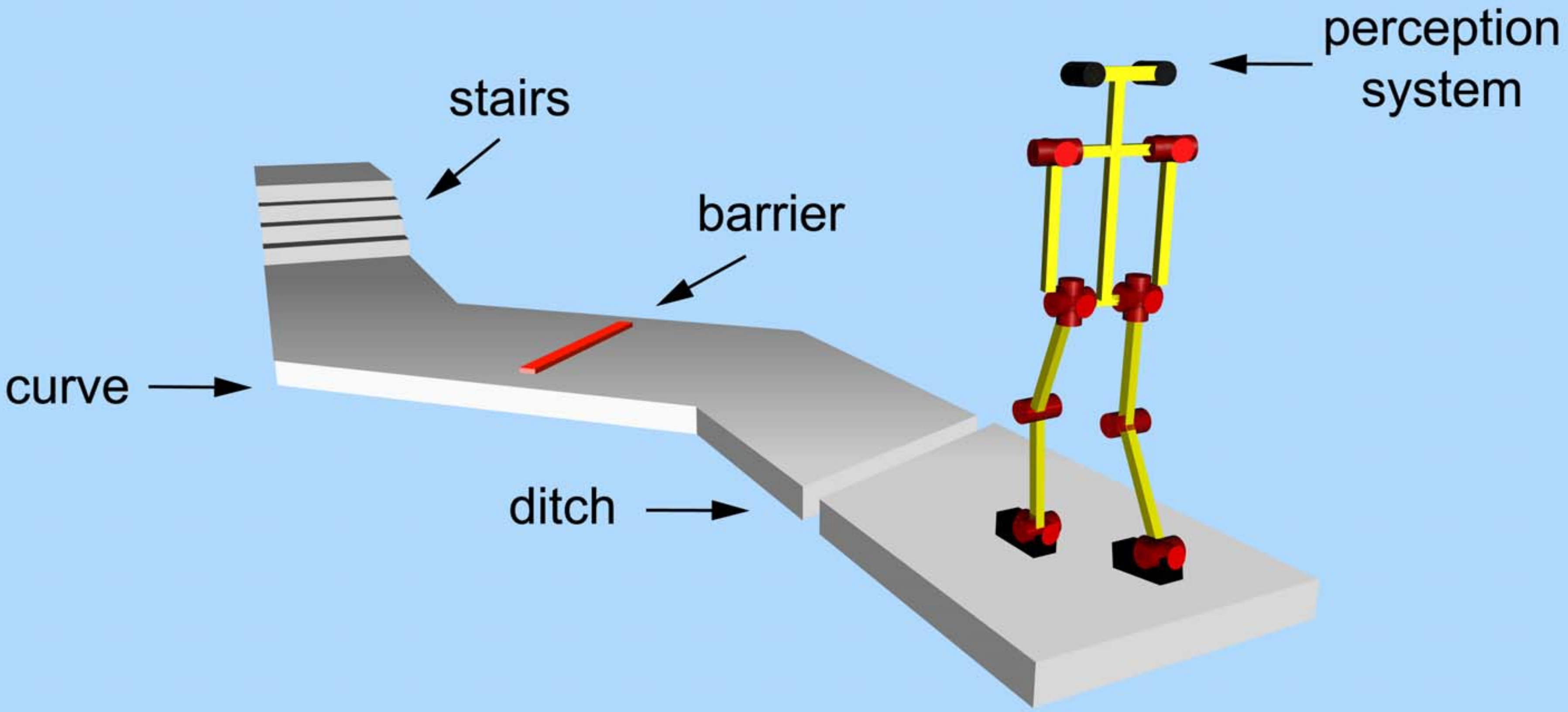
Behaviour based on *(i) intention and (ii) internal intelligence*, i.e. no human intervention required

Intermediate Goal of this Research

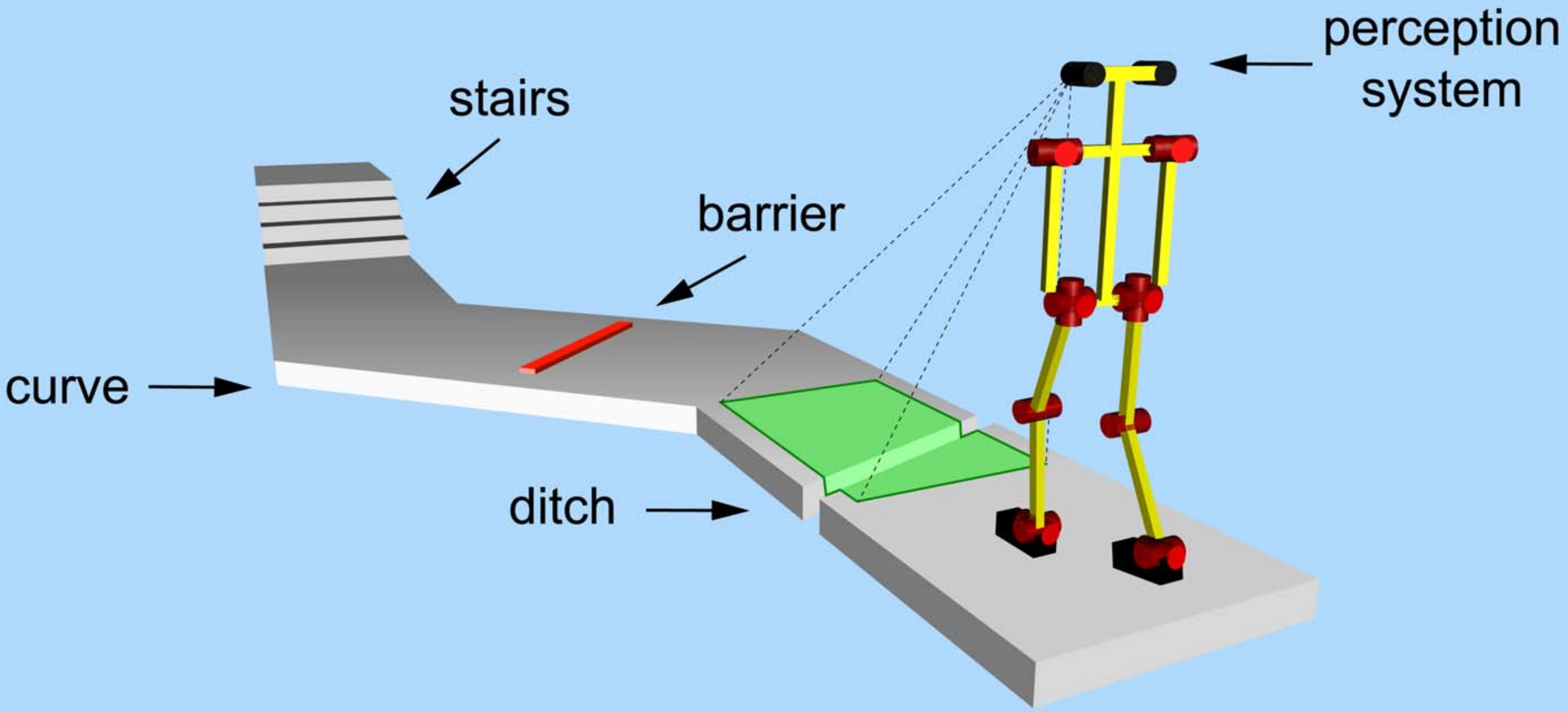
"Continuous, stable, safe and goal-oriented biped walking in partially unknown 3-D indoor environments"

- **Demonstration of "intelligent" walking capabilities**

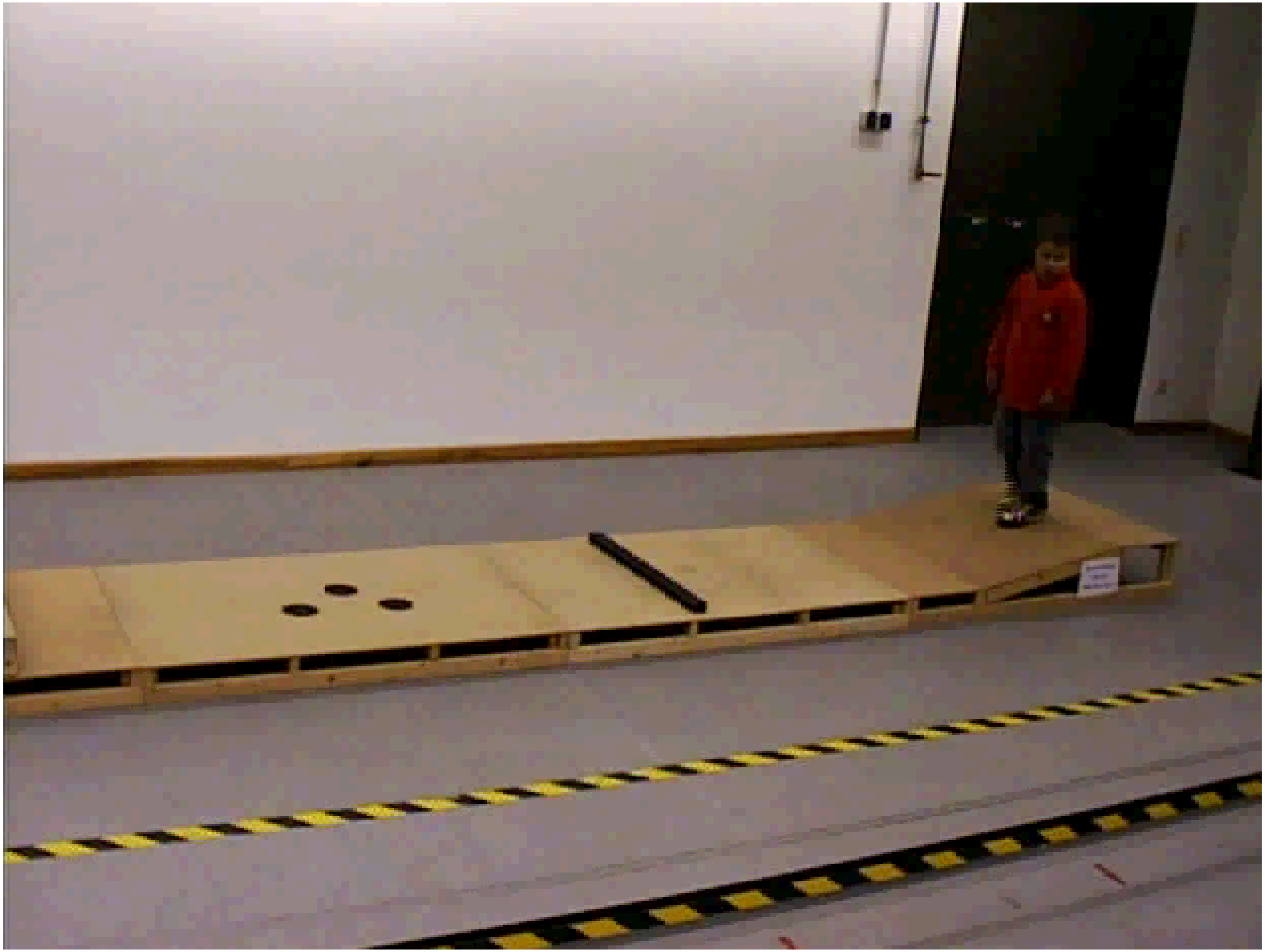
Prototype Scenario of this Research



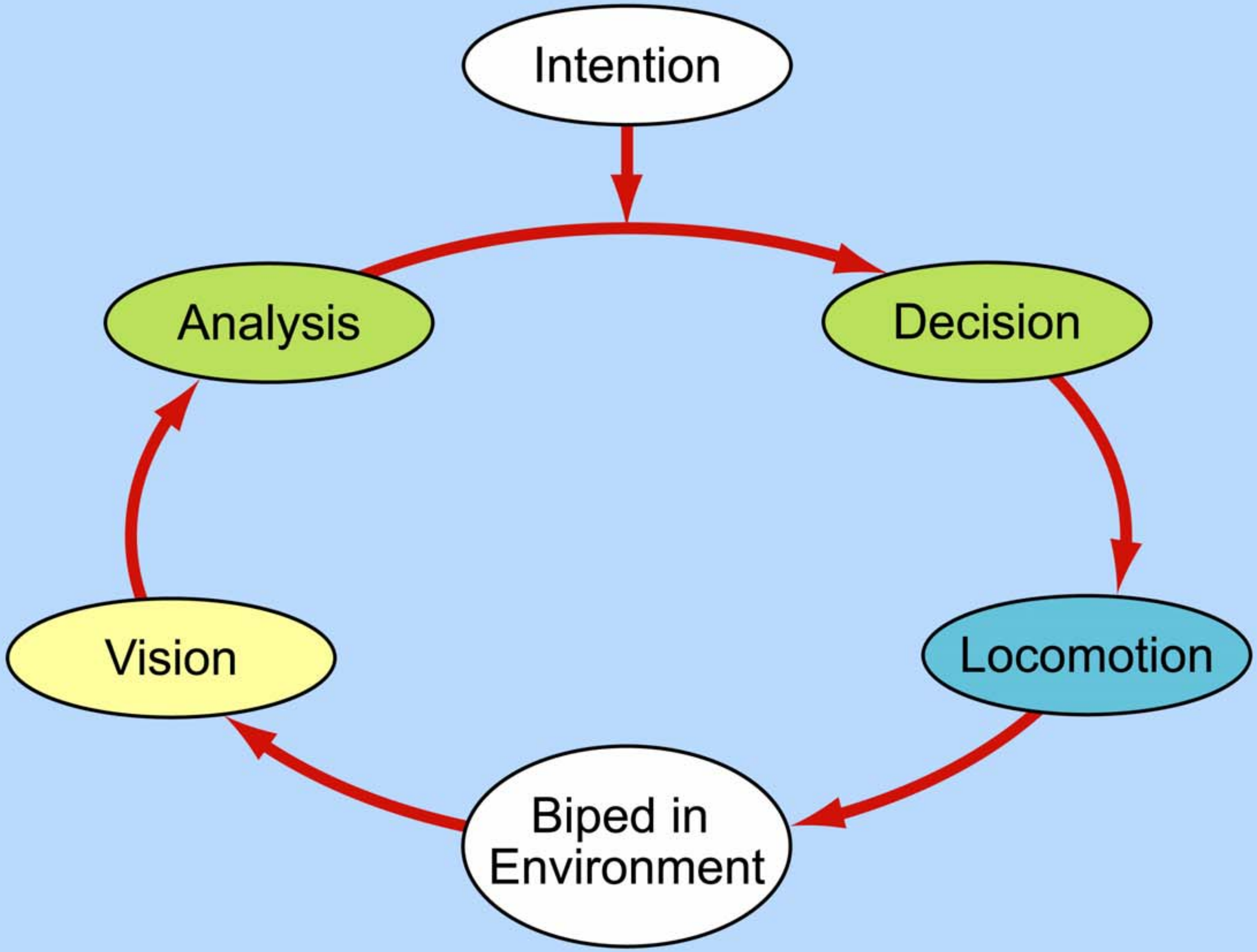
“The view anticipates our steps”

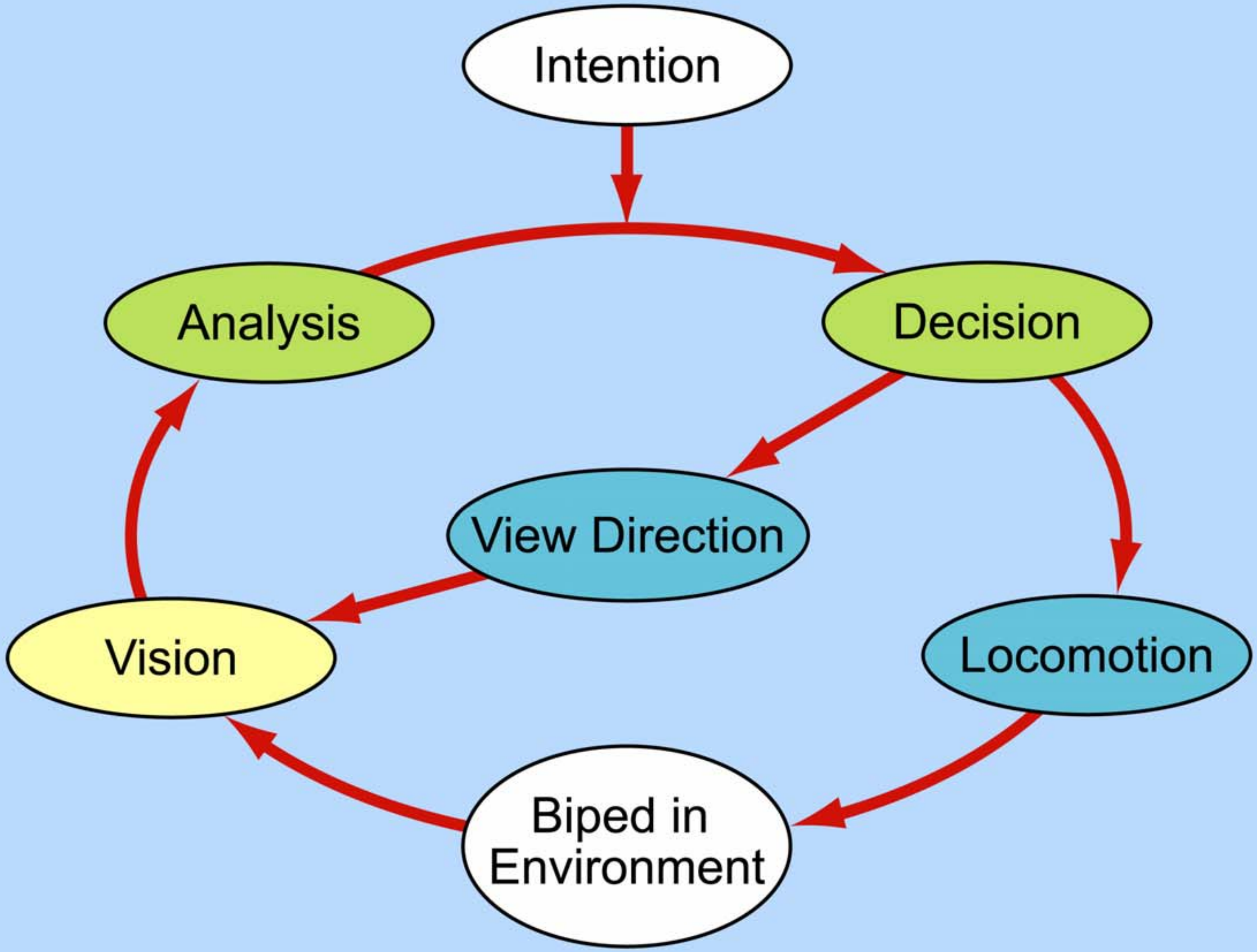


❖ ***A. E. Patla et al., Univ. of Waterloo, ~ 2000***

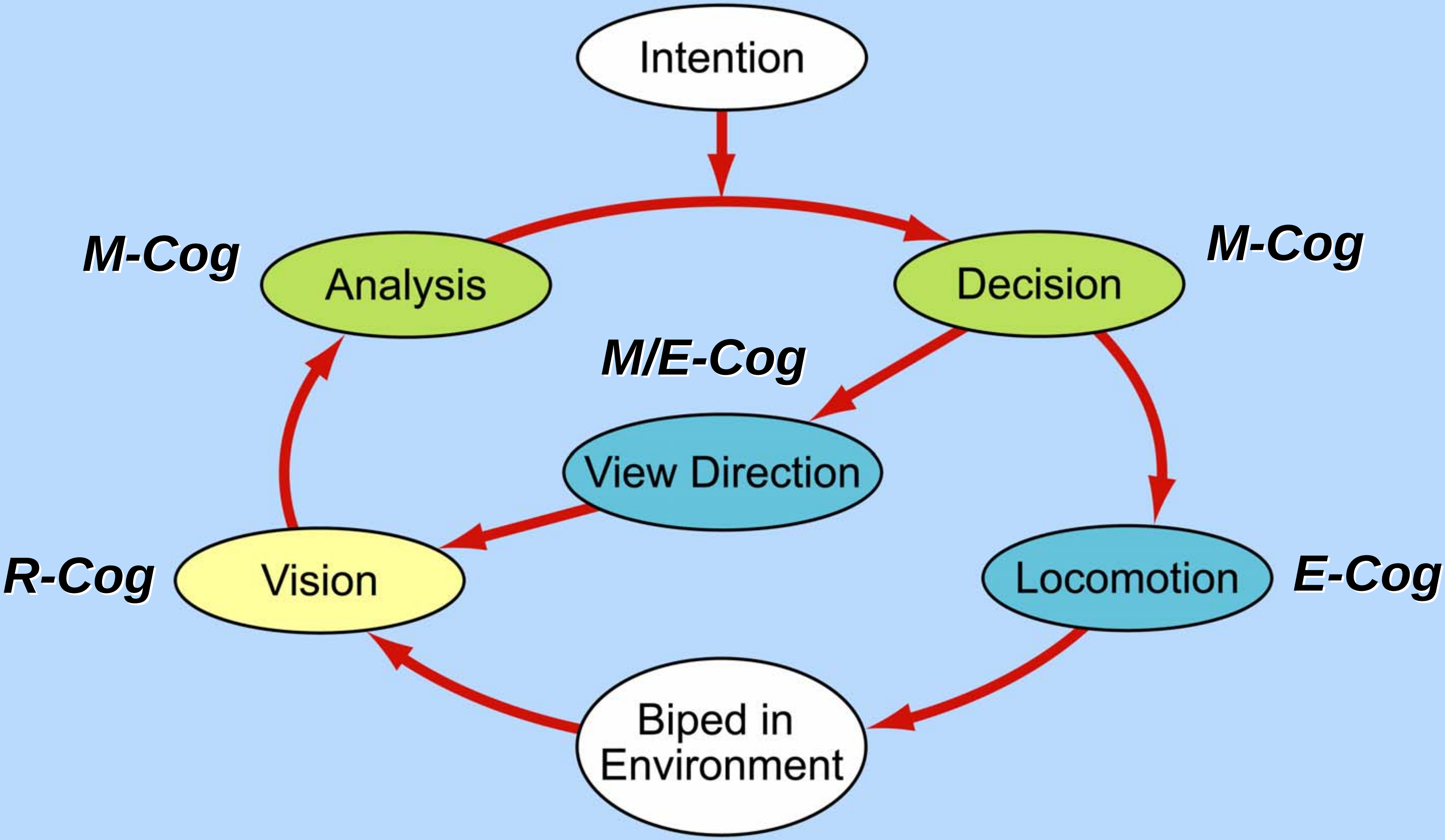


Observing a Human Walker . . . .


Intention
Analysis
Decision
Vision
Locomotion
Biped in
Environment

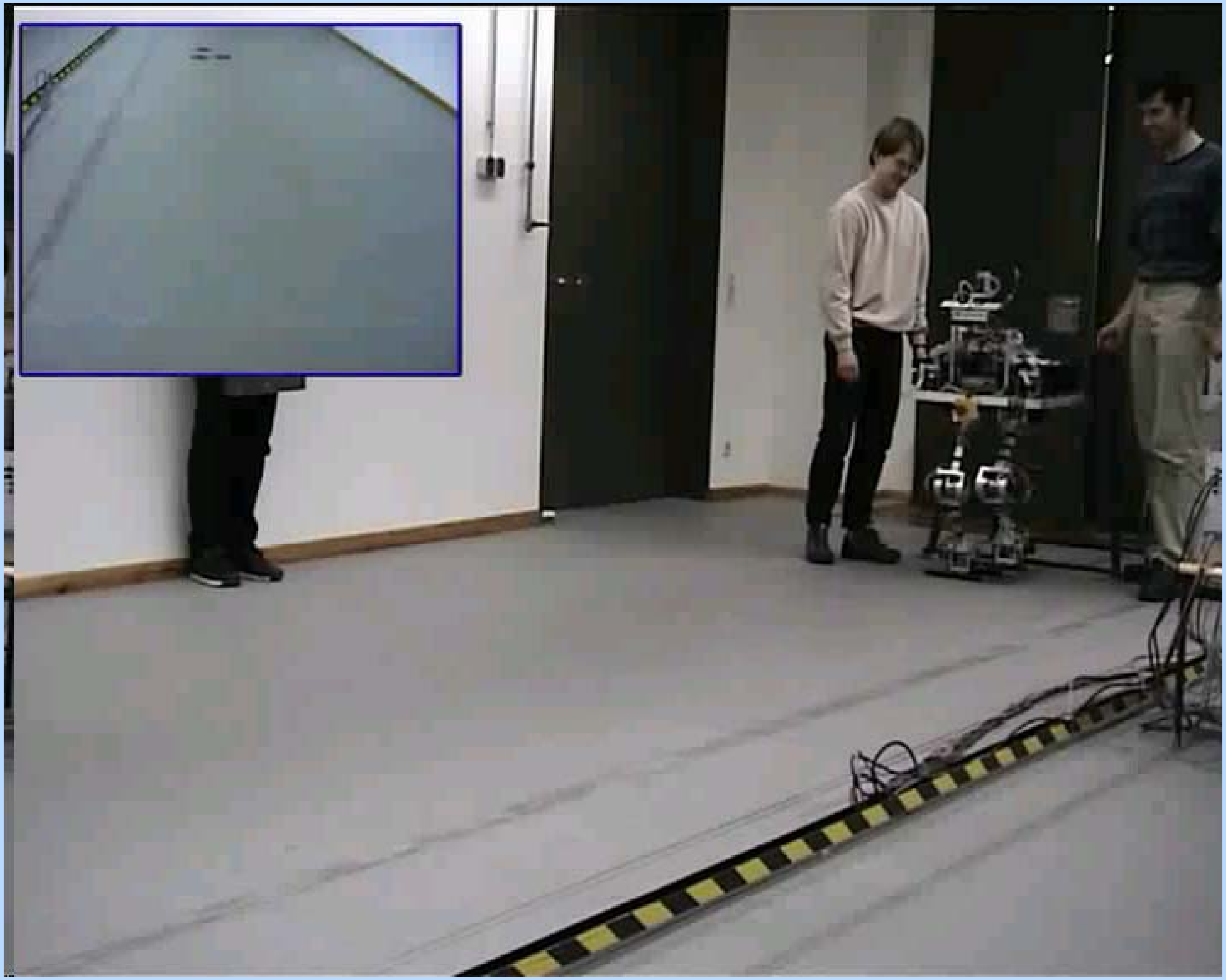


Augmented Perception-Action-Cycle



Perception-Action-Cycle
and Artificial Cognitive Functionalities

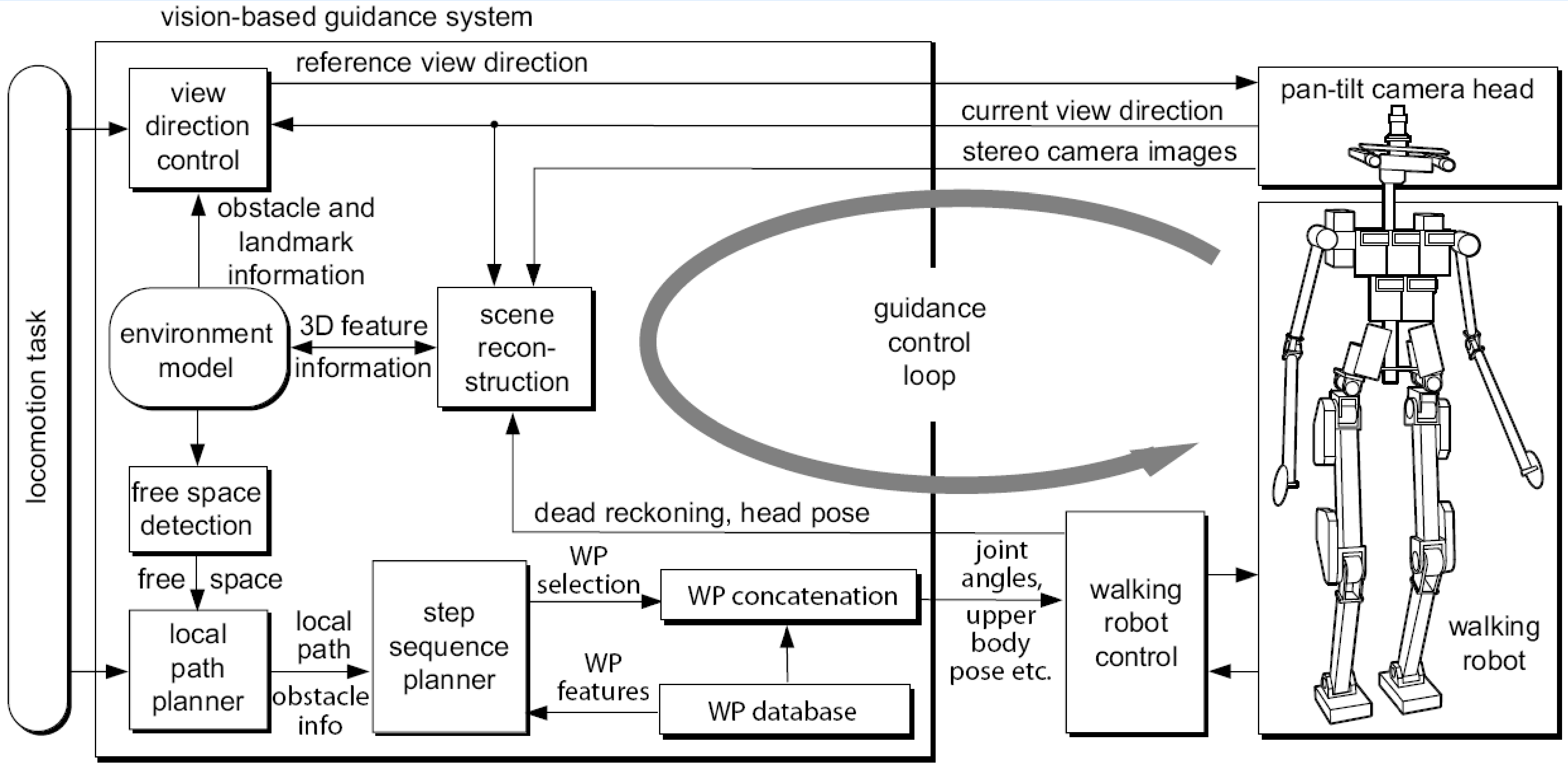
http://www.lsr.ei.tum.de/movies/IBART.avi



Perception-based 2D-Walker i*BARt-UH*

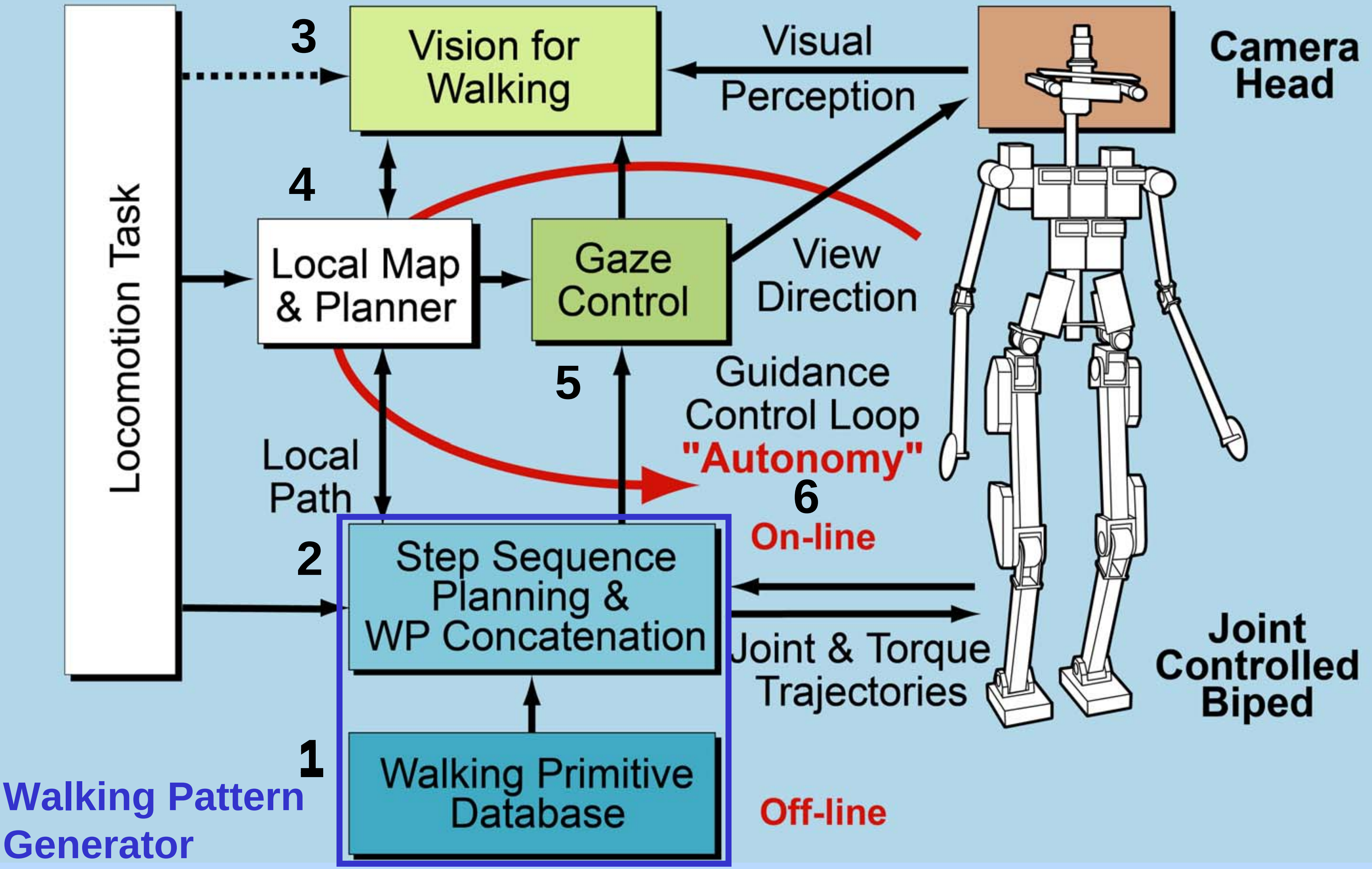
Obstacle Avoidance and Step Trace Following

Architecture and Modules of the Guidance Control System



❖ *J. Denk, G. Schmidt*
Walking Primitive Databases for Perception-Based Guidance Control of Biped Robots.
In Fundamental Issues in Control, Special Issue ECC'07, European Journal of Control, Vol.13, 2007, pp. 171 - 188

Guidance Control Architecture



Contents of Lecture

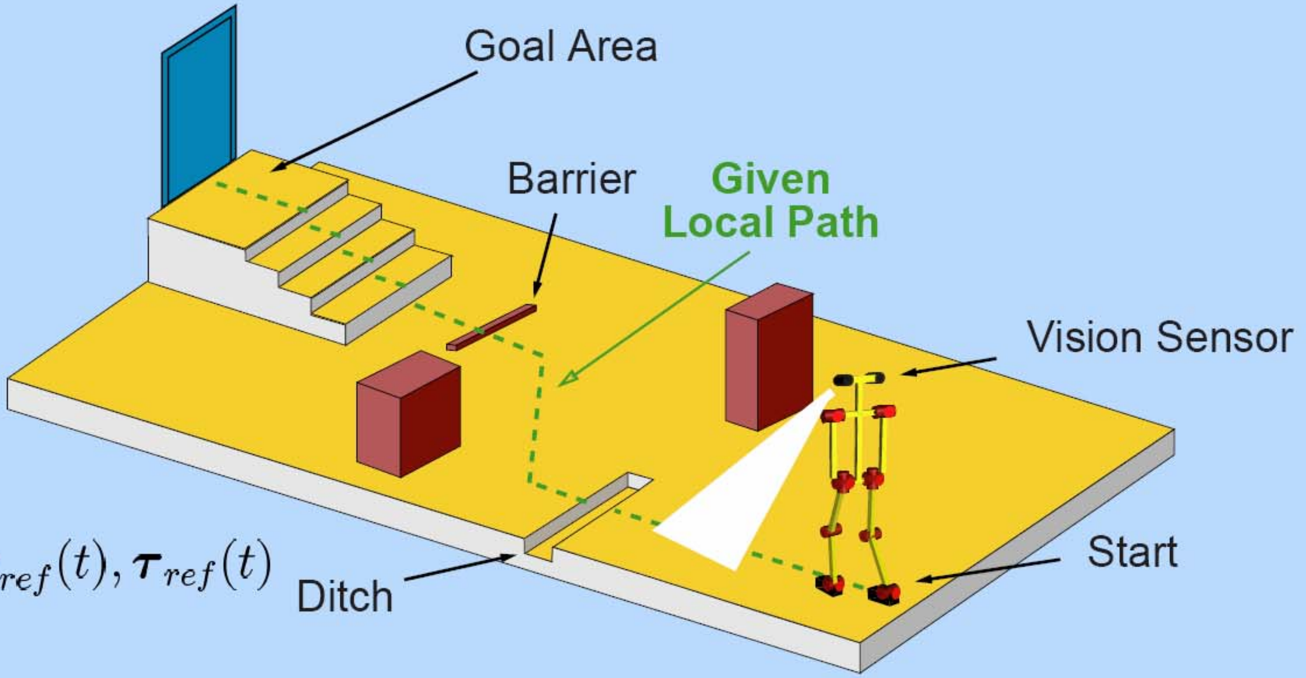
1 + 2

Walking Pattern Generation for Perception-Based Locomotion

- ***J. Denk, G. Schmidt***

Walking Primitive Databases for Perception-Based Guidance Control of Biped Robots.
In Fundamental Issues in Control, Special Issue ECC'07, European Journal of Control, Vol.13, 2007, pp. 171 - 188

Concept and Basic Approach



Walking Pattern $\boldsymbol{q}_{ref}(t), \boldsymbol{\tau}_{ref}(t)$

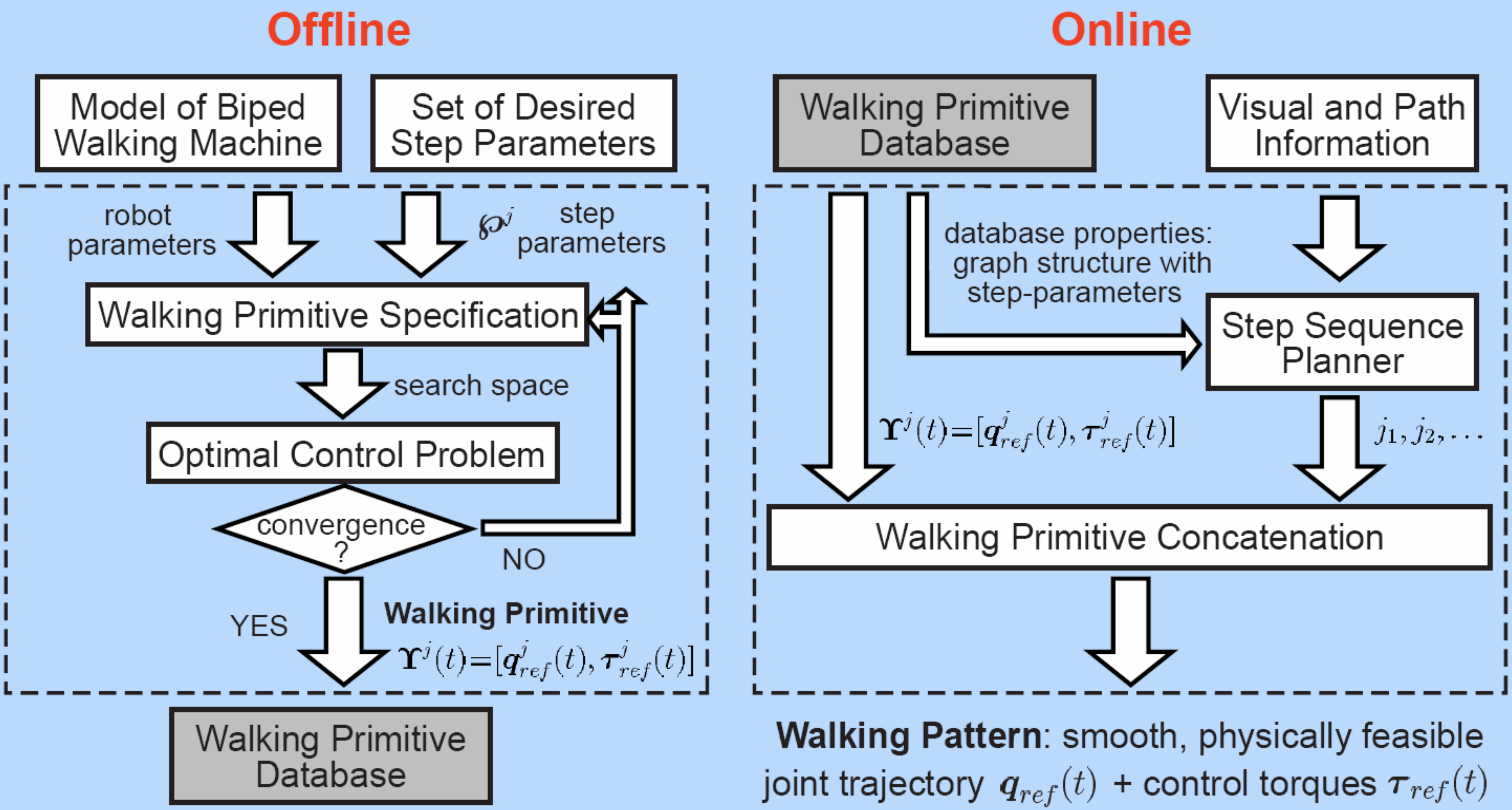
- physical feasibility
- posture stability

Our approach to Pattern generation:

Off-line: Synthesis of Walking Primitives $\Upsilon^j(t) = [\boldsymbol{q}^j_{ref}(t), \boldsymbol{\tau}^j_{ref}(t)], \;\; j = 1, \ldots, M$

On-line: Concatenation of appropriate WPs into a Walking Pattern

Generation Approach - Overview



Walking Pattern: smooth, physically feasible joint trajectory $q_{ref}(t)$ + control torques $\tau_{ref}(t)$

1

The Walking Primitive Database

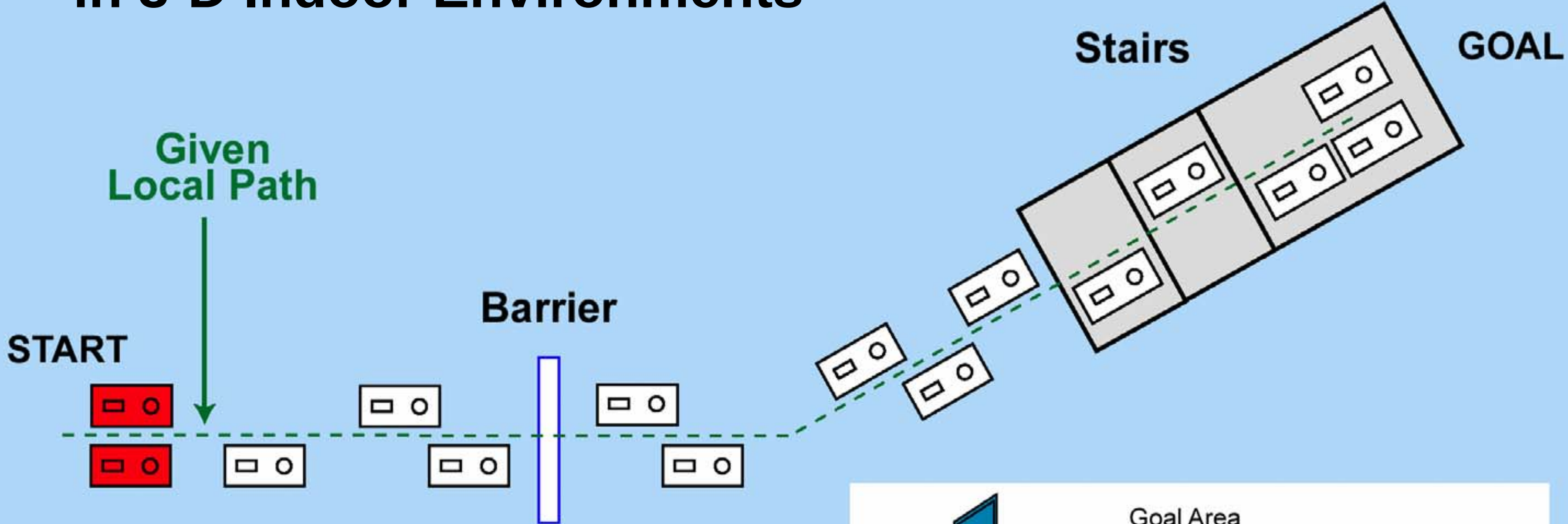
Offline Synthesis

1 a

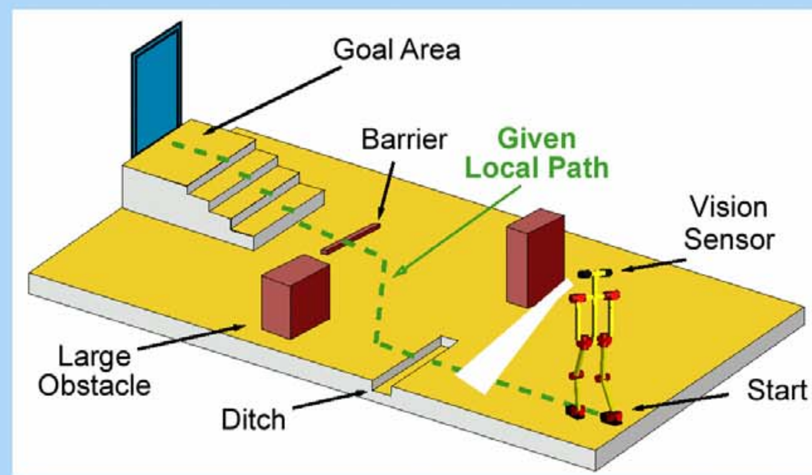
Defintion of Primitives for Continuous Biped Walking

Basic Walk Behaviours

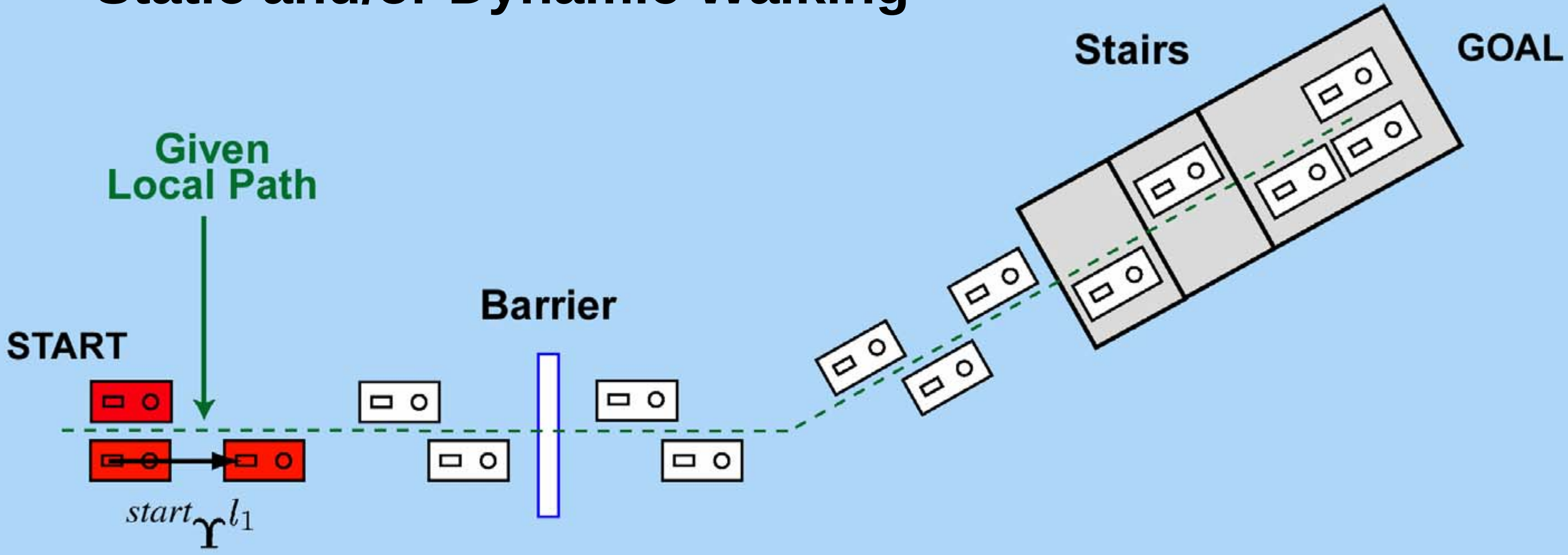
Locomotion Capabilities Required by Biped in 3-D Indoor Environments



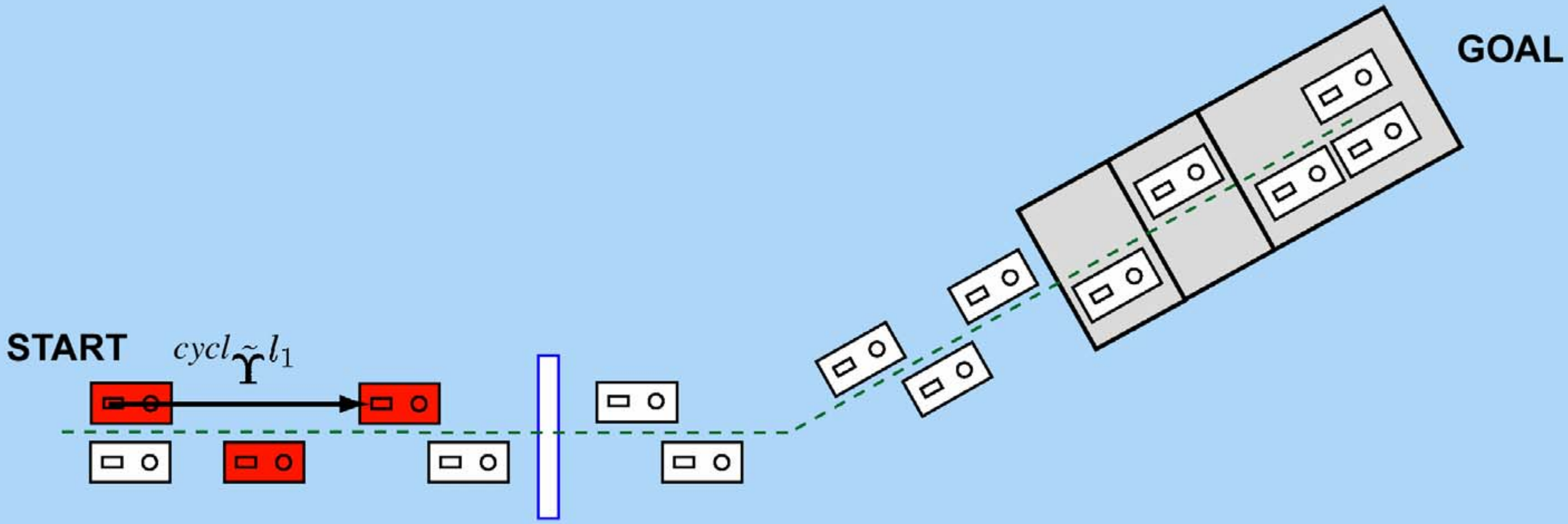
- start and stop walking
- normal walk
- change step-length
- stride over small obstacles
- make direction changes
- step on platform, climb stairs



Typical Primitives for Continuous Static and/or Dynamic Walking



- start-/stop-primitive
- cyclic primitive
- transition primitive
- obstacle primitive combination
- curve primitive combination
- stair primitives



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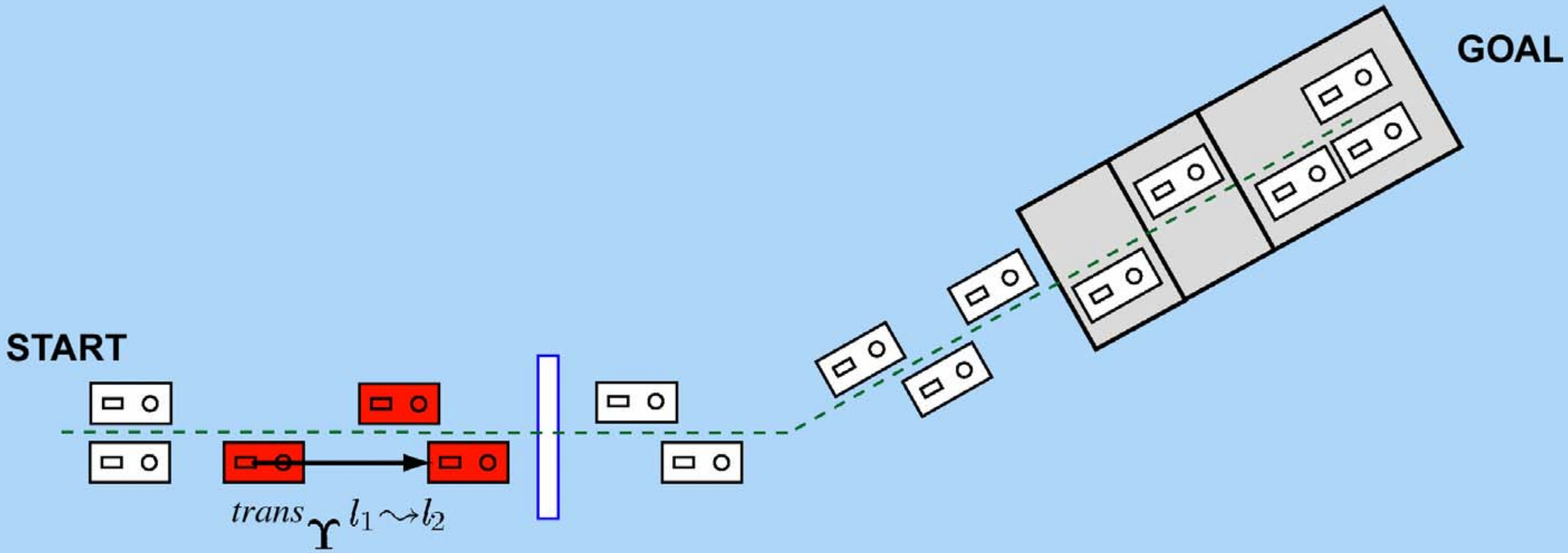

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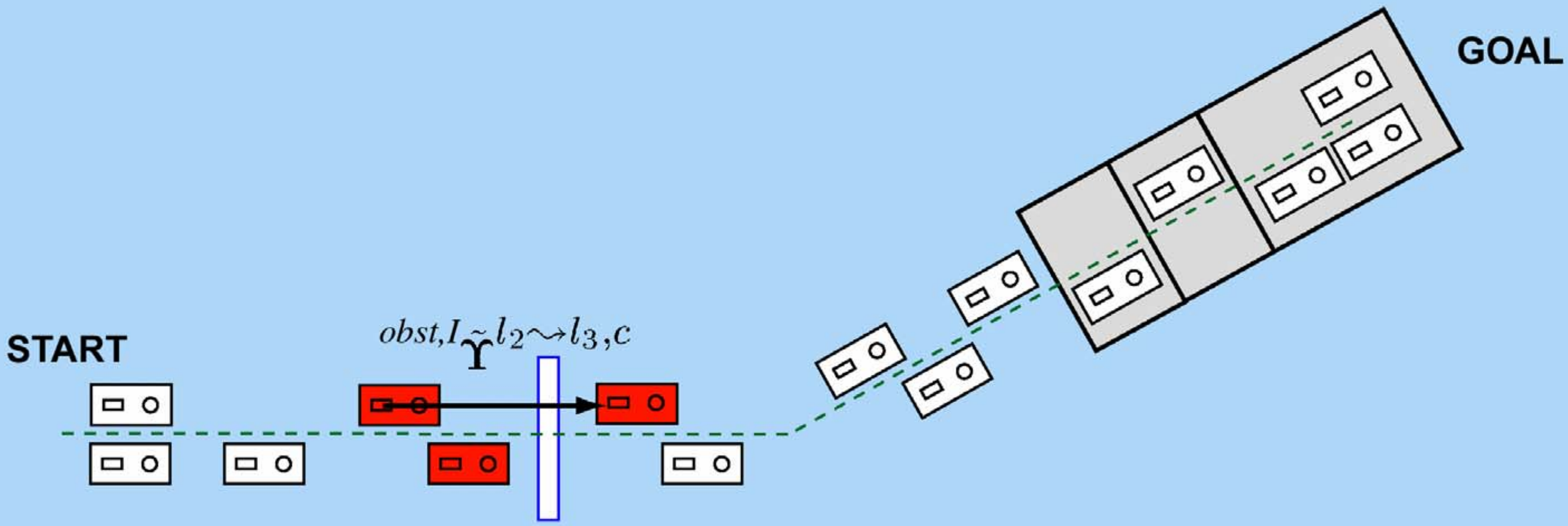

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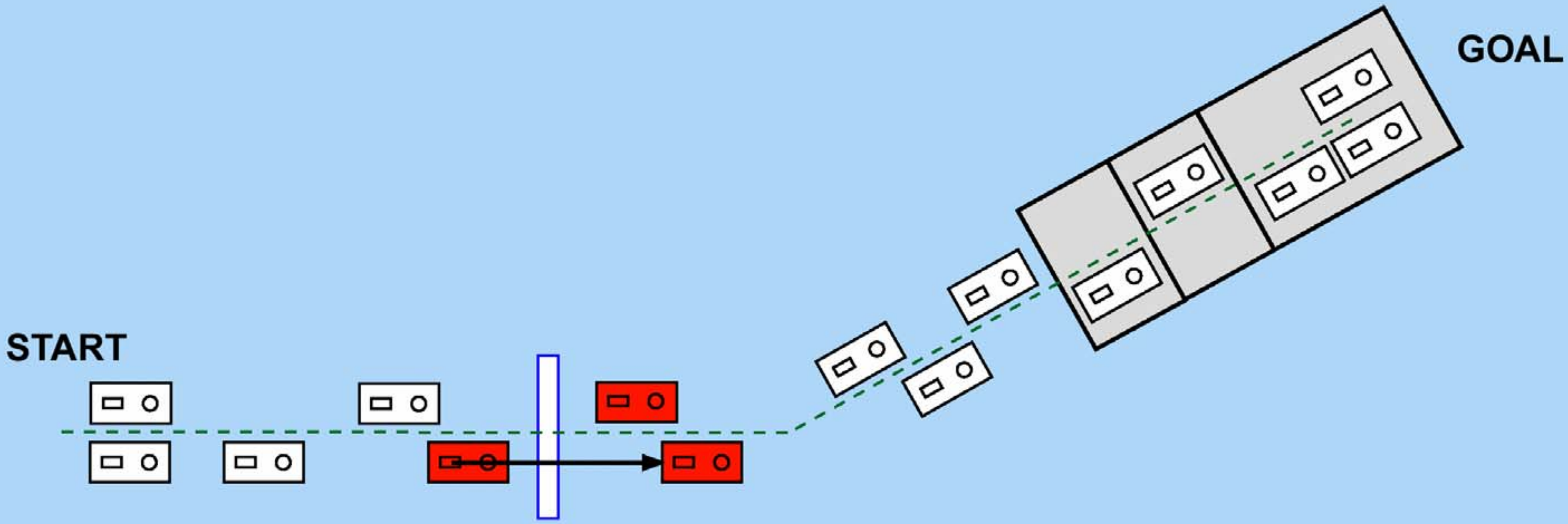
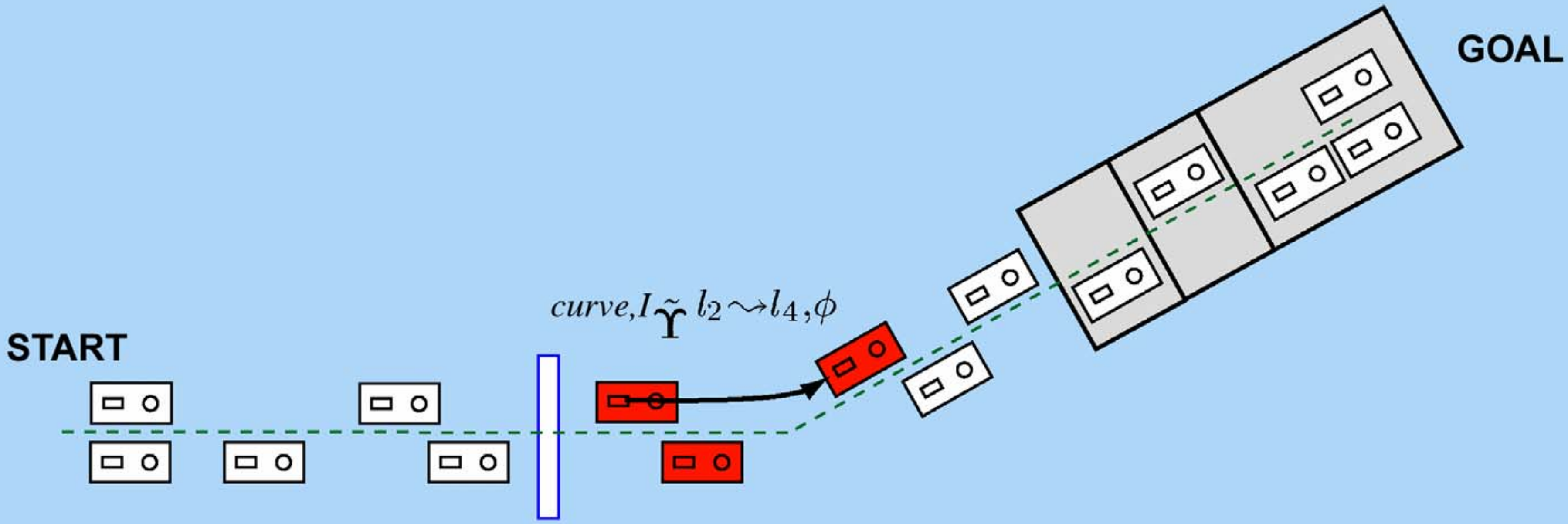


$${}^{obst,II}\Upsilon_{l_3 \rightsquigarrow l_2, c}$$

- start-/stop-primitive
- cyclic primitive
- transition primitive
- obstacle primitive combination
- curve primitive combination
- stair primitives



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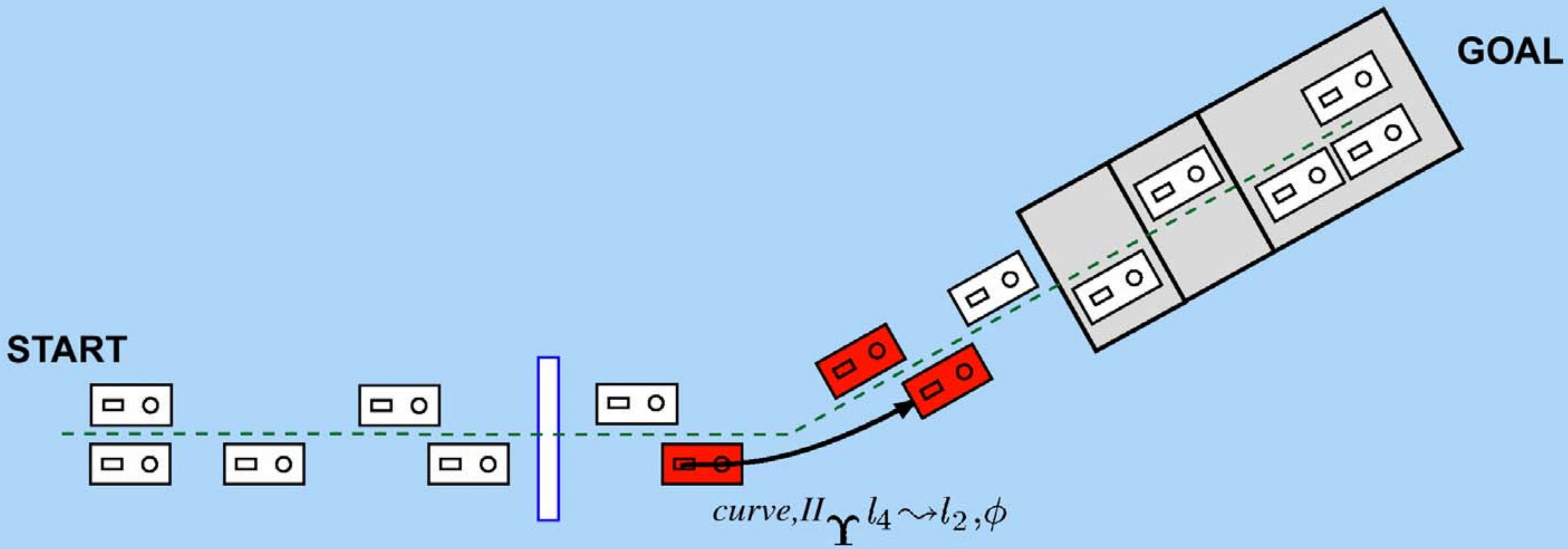
- stair primitives



- start-/stop-primitive
- cyclic primitive
- transition primitive
- obstacle primitive combination
- curve primitive combination
- stair primitives

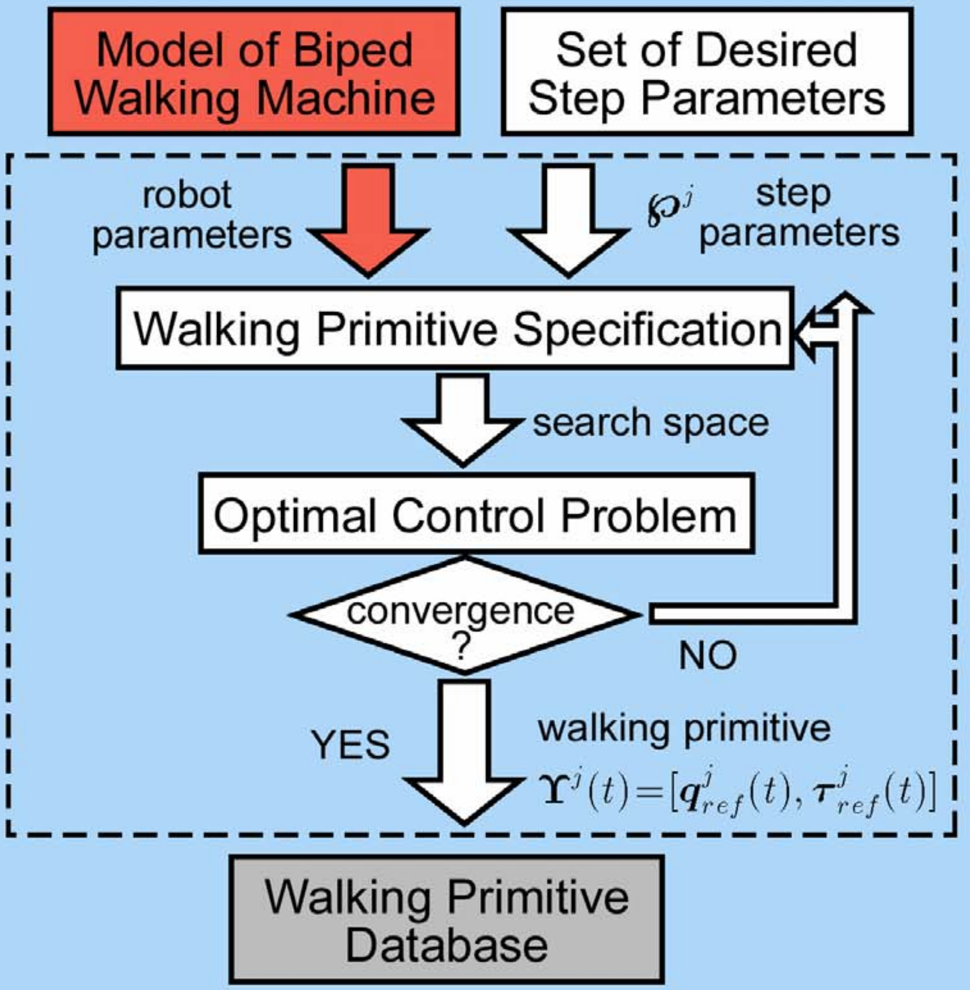
1 b

Computation of Joint and Control Torque Trajectories

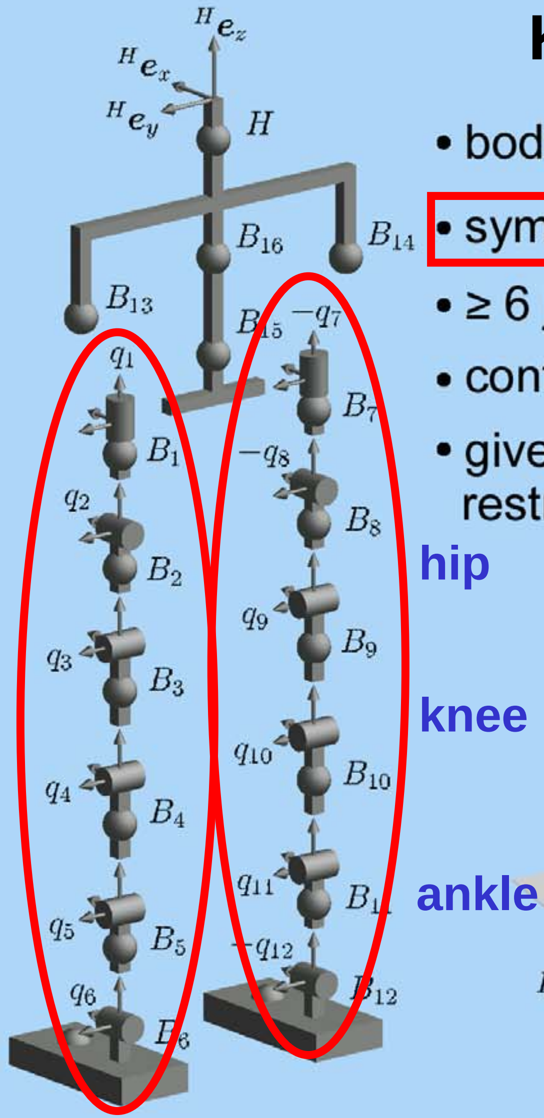
Physical Aspects

❖ *J. Denk , G. Schmidt*
Synthesis of Walking Primitive Databases for Biped Robots in 3D-Environments, Proc. IEEE Int. Conf. on Robotics and Automation, ICRA 2003, pp. 1343 - 1349.

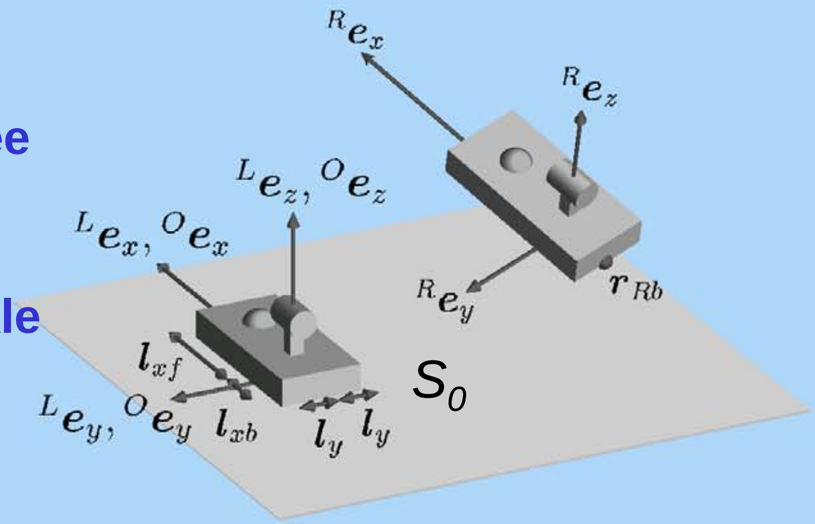
Walking Primitive Synthesis



Kinetic Model of the Biped



- bodies $B_i, i=1 \ldots N_b$ connected by driven joints $q_i, \tau_i, i=1 \ldots N_j$
- symmetry of left and right side
- ≥ 6 joint-DOF in each leg
- contact beween foot and ground sufficiently inelastic
- given masses, inertia-tensors, friction coefficient and restrictions on joint-angles, joint-velocities and joint-torques



joint-angle-vector:

$$q = [q_l, q_r]$$

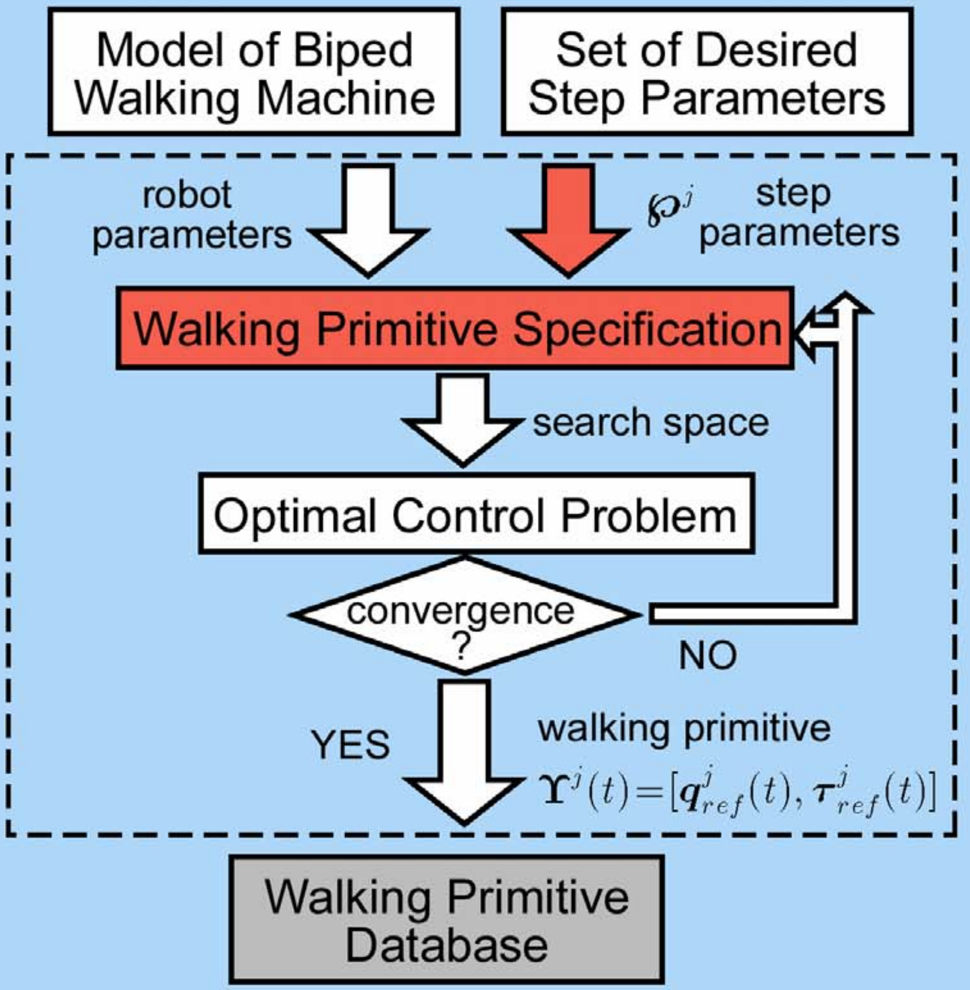
pose of left/right foot:

$$p_{L/R} = [r_{L/R}, \phi_{L/R}]$$

posture of biped:

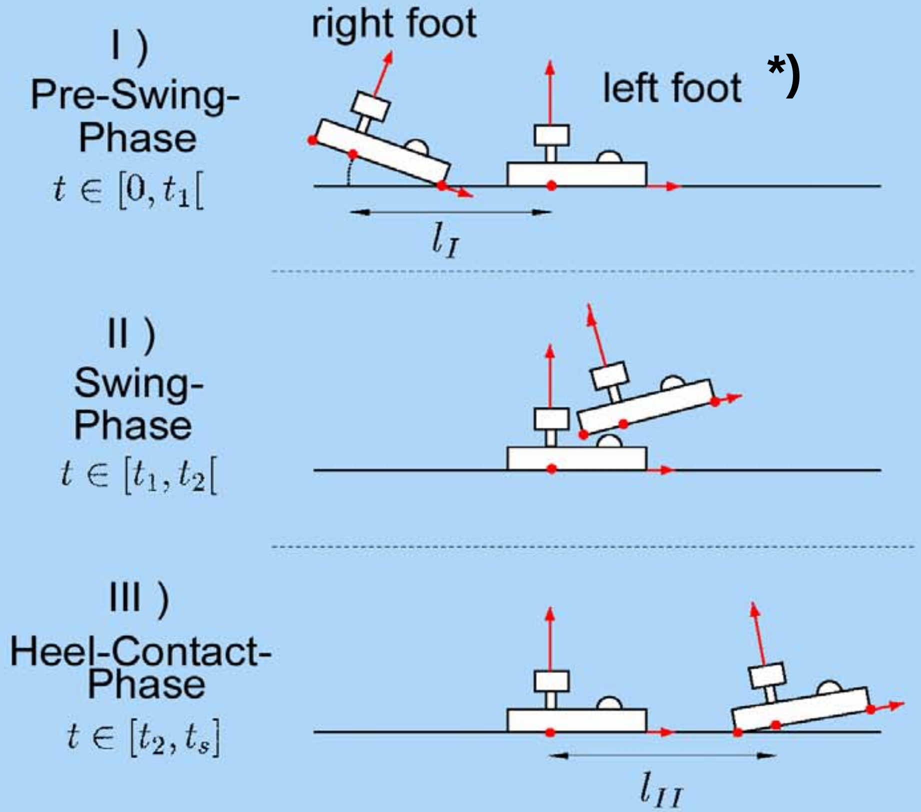
$$q_g = [q, p_L]$$

Specification of Walking Primitive Properties



Walking Primitive Motion Phases, Kinematics and Dynamics

Motion Phases



*) left foot resides flat on ground

Kinematics

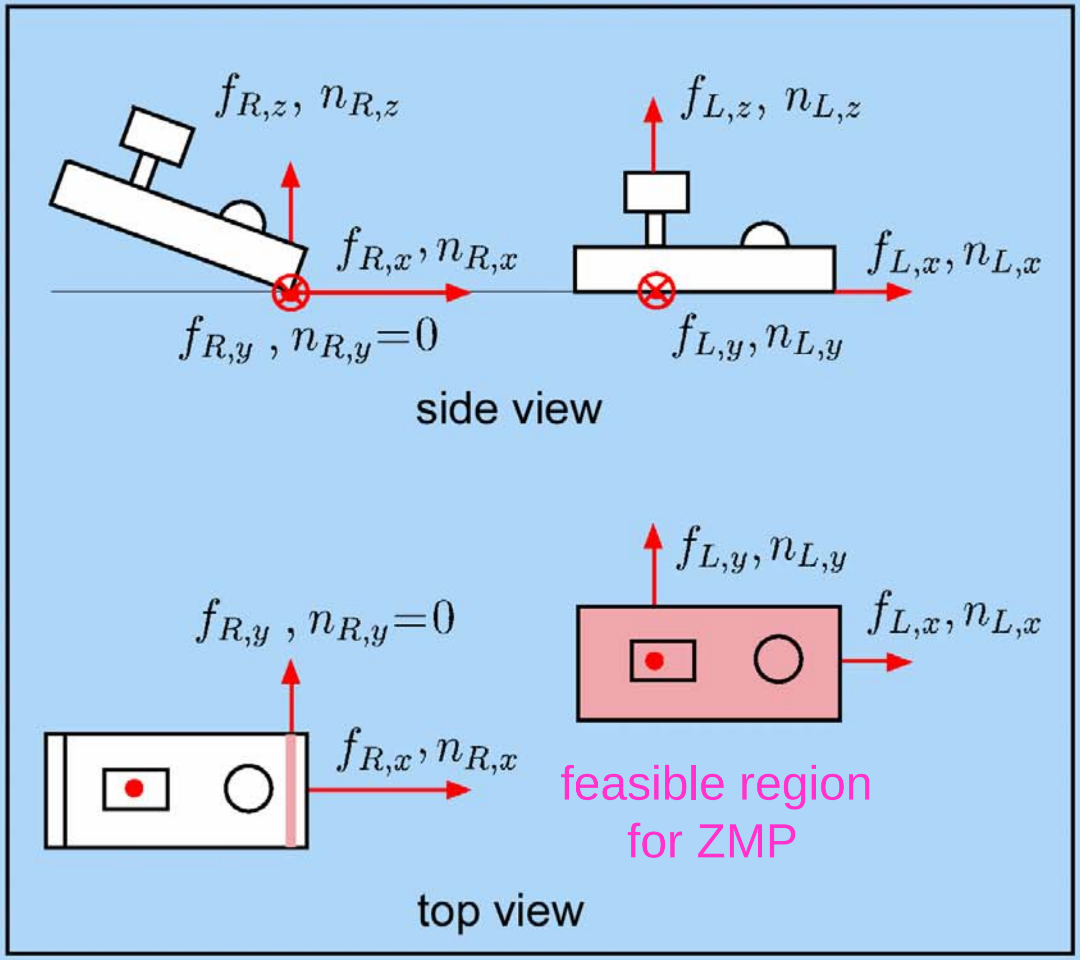
- step-parameters: length l_I, l_{II}; height c; phase transition times t_1, t_2, t_s, ...
- continuous system state
  $\Rightarrow$ no jumps in velocities
  $\Rightarrow$ avoidance of impacts during heel strike
- avoidance of internal and external collisions by inequality constraints on direct kinematics

Dynamics

- specific rigid body models for each phase assuming bilateral rigid body contacts

Conditions for Contact Stability

Example: Pre-Swing-Phase I)



Unilaterality Conditions:

$$\boxed{f_z \geq 0}$$

contact force not attractive

ZMP-Conditions:

$$\boxed{r_{p,x} = -\frac{n_y}{f_z}, \quad r_{p,y} = \frac{n_x}{f_z}}$$

$\boldsymbol{r_P}$ = ZMP inside supporting area

Friction Conditions:

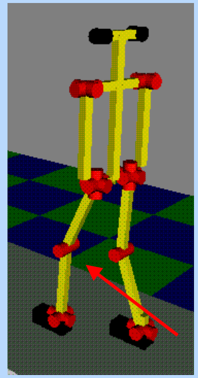
$$\boxed{\sqrt{f_x^2 + f_y^2} + \left|\frac{n_z}{\kappa}\right| \leq \mu f_z}$$

no slippage

Conditions for Concatenation of Walking Primitives

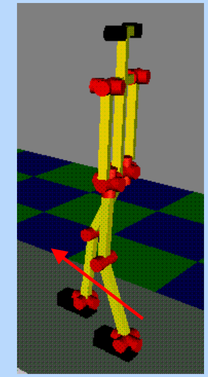
(i) Walking primitive for **right foot swinging**:

$$\boldsymbol{q}(t) = [\boldsymbol{q}_l(t), \boldsymbol{q}_r(t)]$$



Symmetric primitive for **left foot swinging** by mapping:

$$\tilde{\boldsymbol{q}}(t) = [\boldsymbol{q}_r(t), \boldsymbol{q}_l(t)]$$



Continuous system state → boundary conditions for
- initial joint state $\boxed{\boldsymbol{x}_0 = [\boldsymbol{q}_0, \dot{\boldsymbol{q}}_0]}$
- final joint state $\boxed{\boldsymbol{x}_s = [\boldsymbol{q}_s, \dot{\boldsymbol{q}}_s]}$

(ii) cyclic primitive

$$l_I = l_{II} = a$$

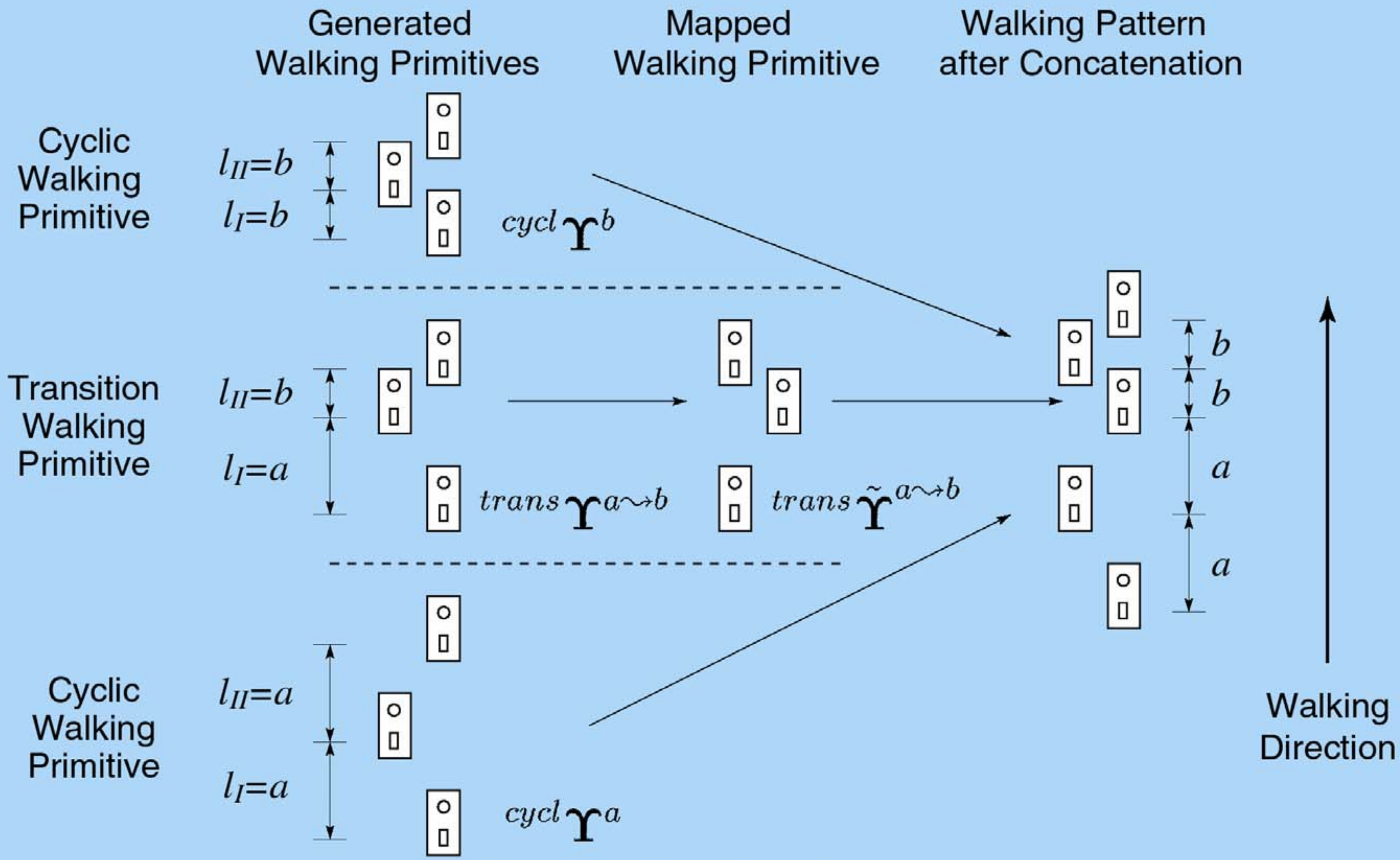
$$\boxed{{}^{cycl}\boldsymbol{x}_s^a = {}^{cycl}\tilde{\boldsymbol{x}}_0^a}$$

(iii) transition primitive

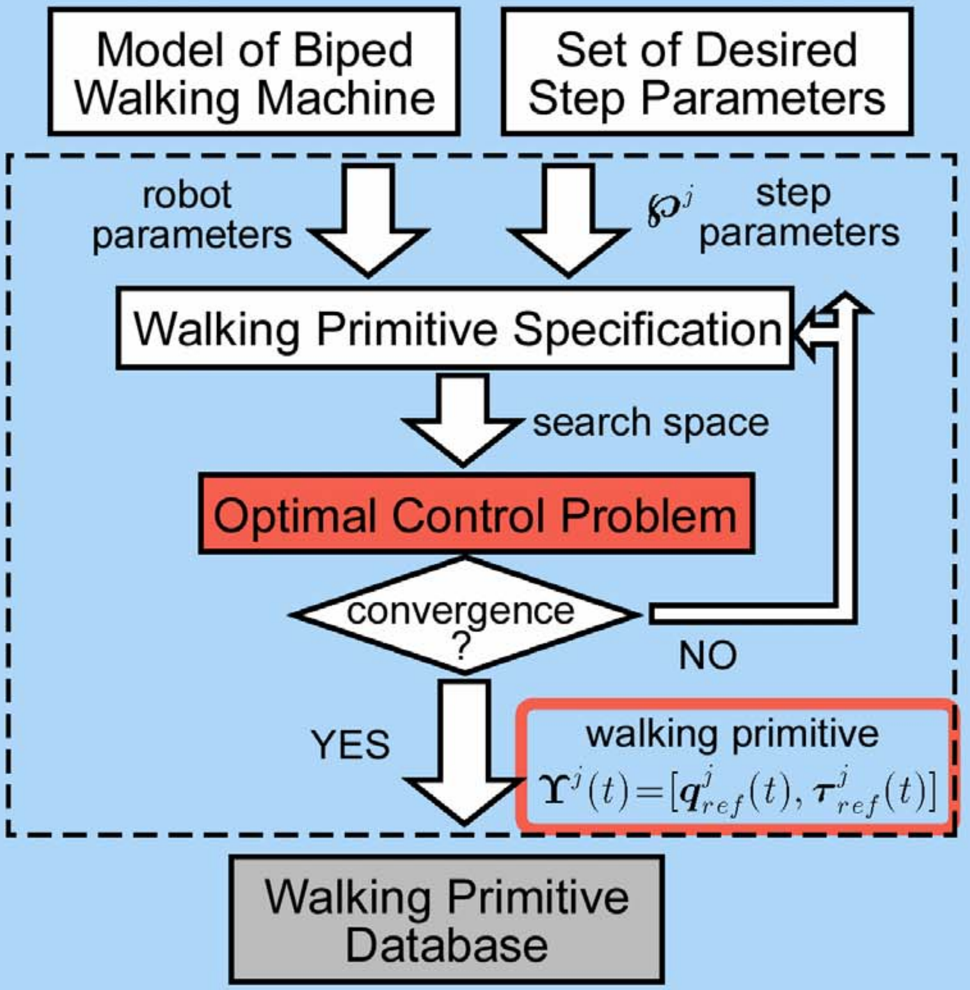
$$l_I = a, \; l_{II} = b$$

$$\boxed{\begin{aligned} {}^{trans}\boldsymbol{x}_0^{a\leadsto b} &= {}^{cycl}\tilde{\boldsymbol{x}}_s^{a\leadsto a} \\ {}^{trans}\boldsymbol{x}_s^{a\leadsto b} &= {}^{cycl}\tilde{\boldsymbol{x}}_0^{b\leadsto b} \end{aligned}}$$

Example of Walking Primitive Concatenation



Computation of Joint + Control Torque Trajectories



3-Phase Hybrid Optimal Control Problem

$$\min_{\boldsymbol{\tau}(t)} \left[\underbrace{\int_0^{t_1} \boldsymbol{\phi}^1(\boldsymbol{x},\boldsymbol{\tau})\,dt}_{\text{Pre-Swing}} + \underbrace{\int_{t_1}^{t_2} \boldsymbol{\phi}^2(\boldsymbol{x},\boldsymbol{\tau})\,dt}_{\text{Swing}} + \underbrace{\int_{t_2}^{t_s} \boldsymbol{\phi}^3(\boldsymbol{x},\boldsymbol{\tau})\,dt}_{\text{Heel-Contact}} \right]$$

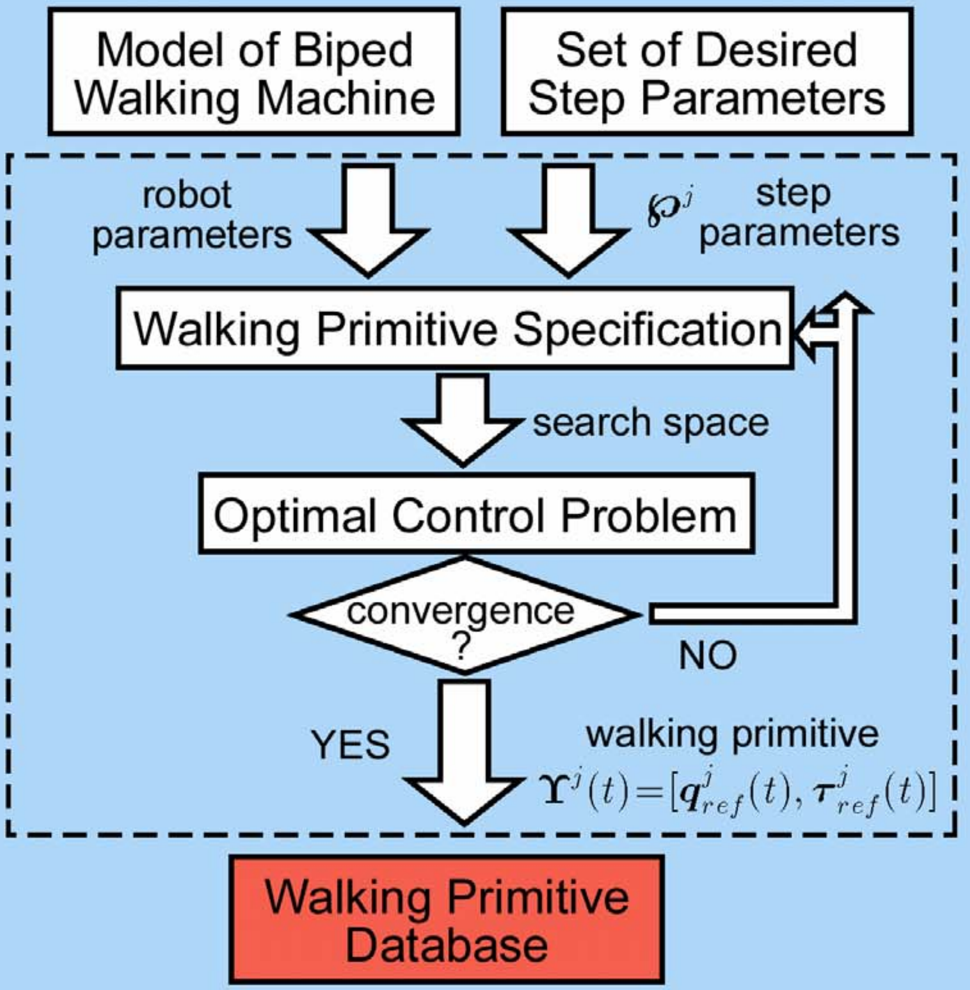
subject to:

- system of ODEs for each phase (*AUTOLEV*)
- contact stability conditions
- constraints for collision avoidance, internal & external
- mechanical and electrical restrictions
- boundary conditions for start/stop, cyclic or transition walking primitives

Typical performance index

$$\boxed{\phi^k = \sum_{i=1}^{N_j} |\dot{q}_i(t)\tau_i(t)|}$$

Absolute mechanical power

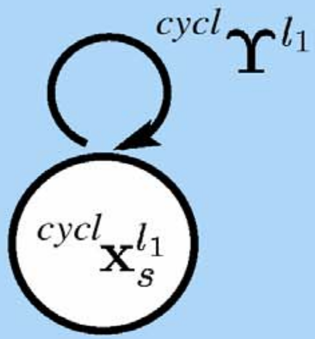


Model of Biped Walking Machine
Set of Desired Step Parameters
robot parameters
$\wp^j$ step parameters
Walking Primitive Specification
search space
Optimal Control Problem
convergence ?
NO
YES
walking primitive
$\Upsilon^j(t)=[\boldsymbol{q}^j_{ref}(t), \boldsymbol{\tau}^j_{ref}(t)]$
Walking Primitive Database

1 c

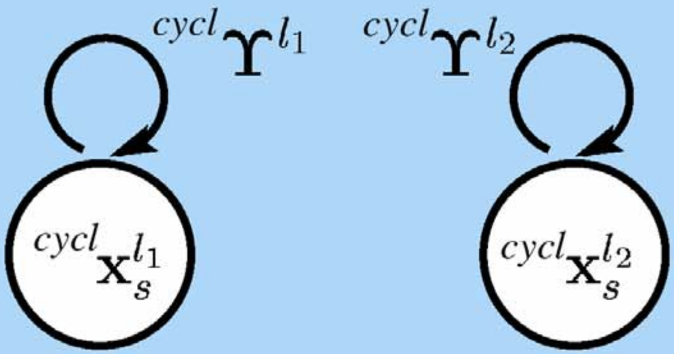
Systematic Procedure for Database Generation

Database Synthesis and Graph Representation

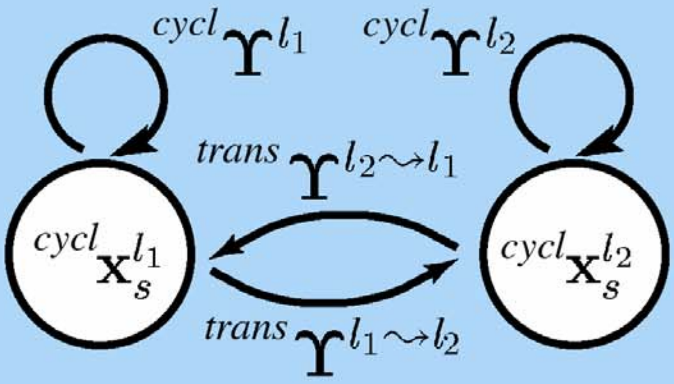


(1) Synthesize **cyclic primitive l_1**

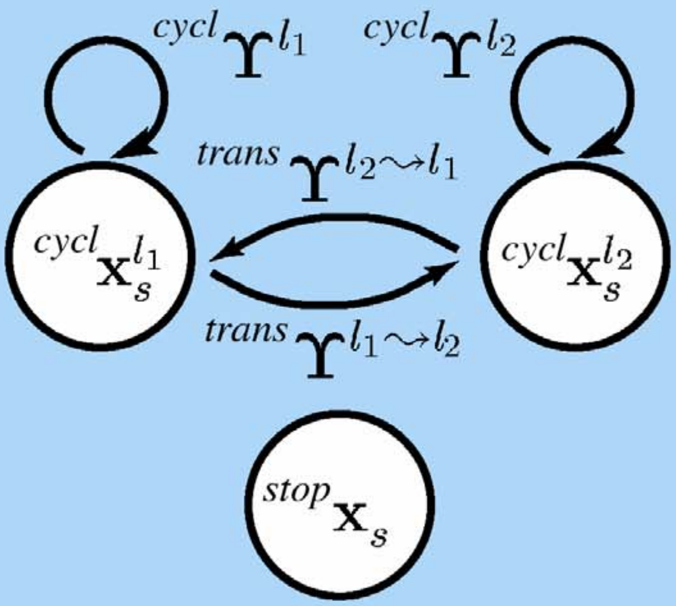
→ initial / final joint state ${}^{cycl}\boldsymbol{x}_s^{l_1} = {}^{cycl}\tilde{\boldsymbol{x}}_0^{l_1}$



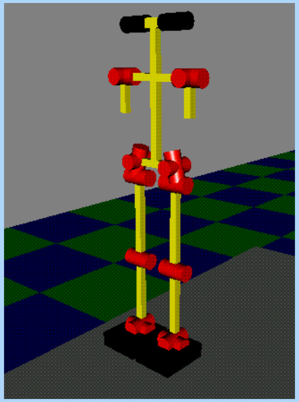
(1') Synthesize **cyclic primitive l_2**

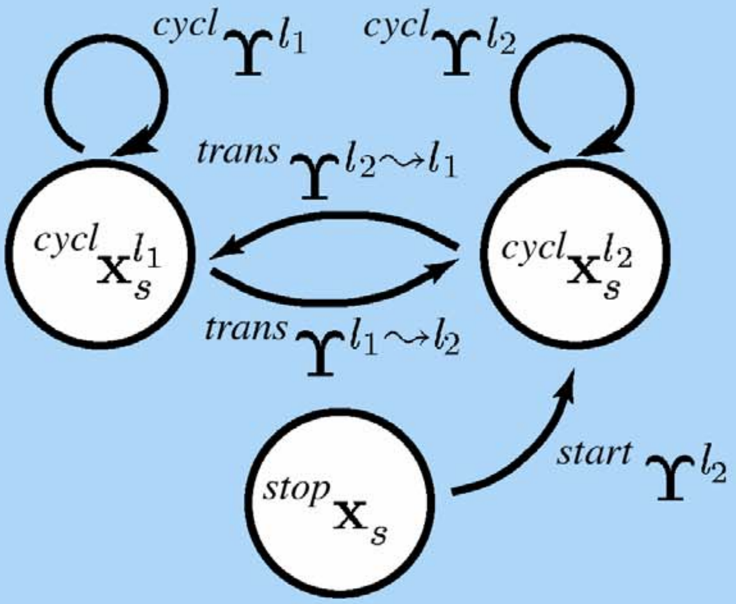


(2) Synthesize **transition primitives**

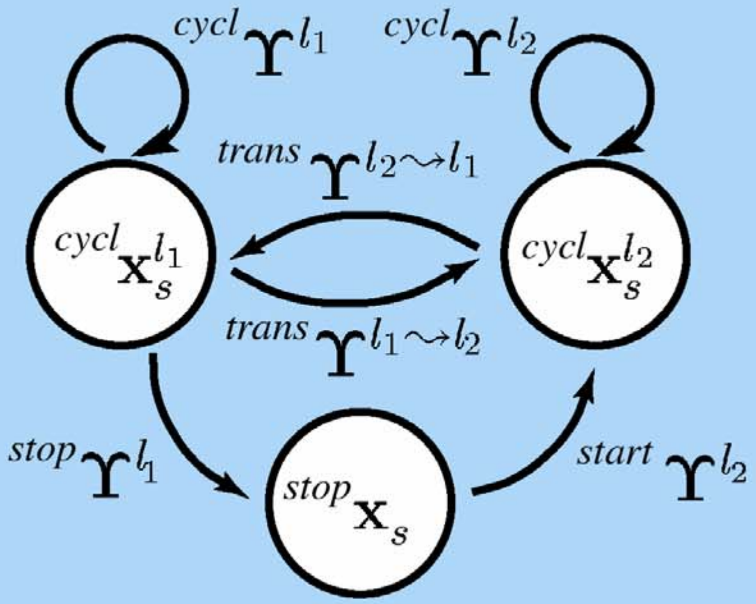


(3) Define joint state for biped in state **stop**

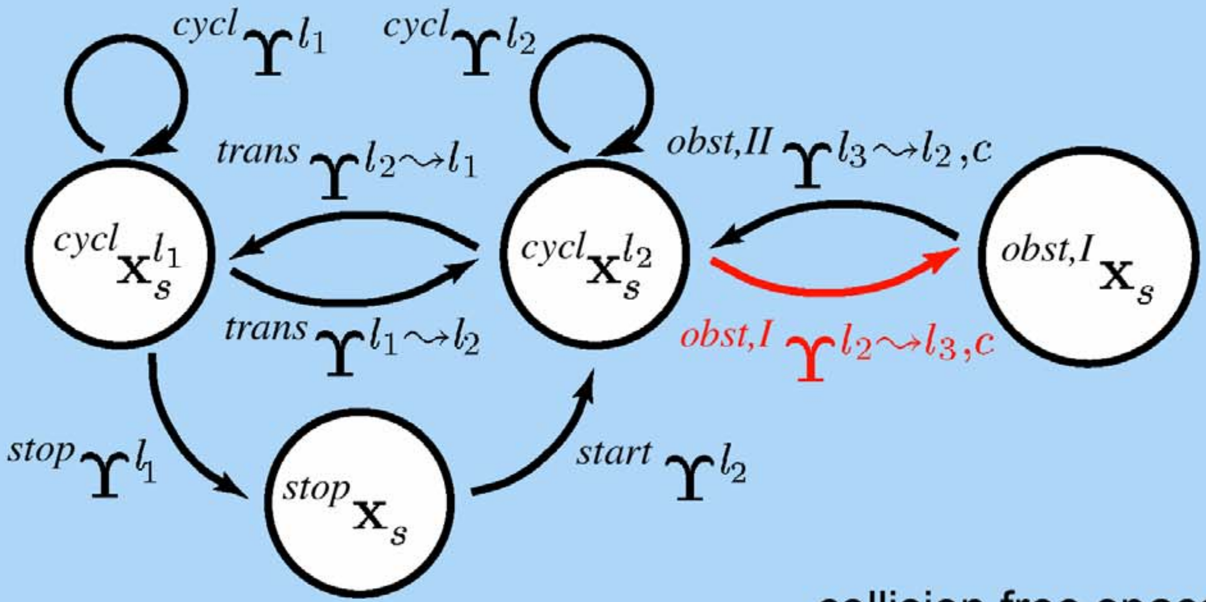




(4) Synthesize **start primitive**

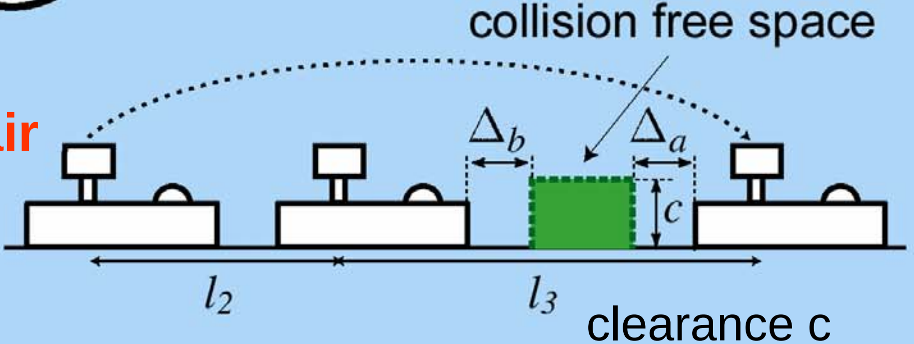


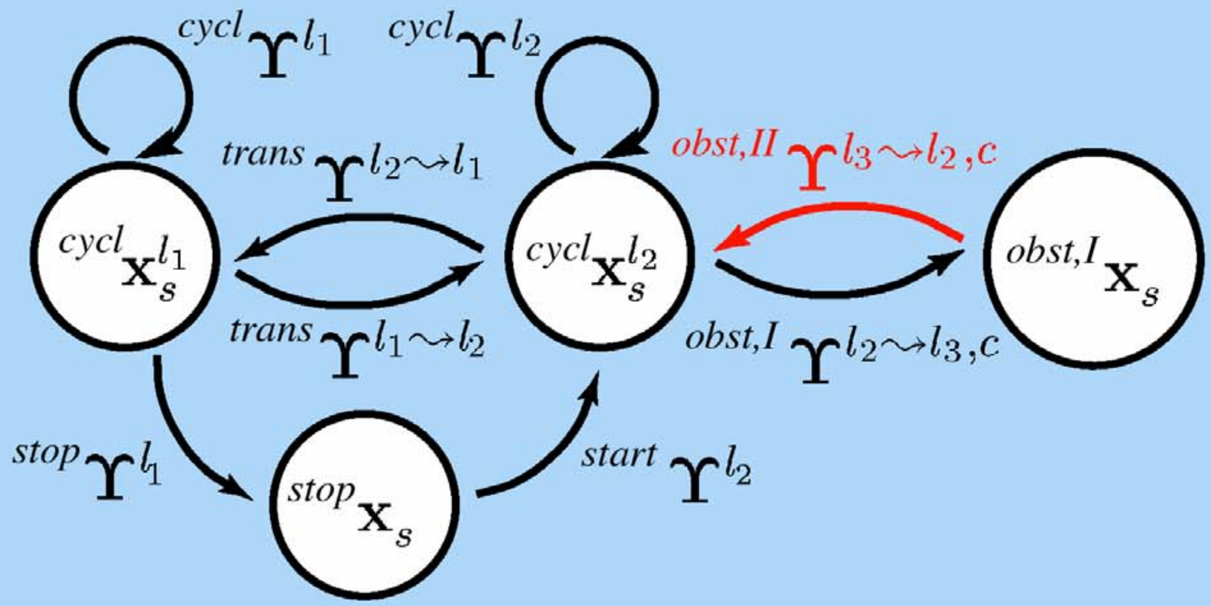
(5) Synthesize **stop primitive**



(6) Synthesize **obstacle primitive pair**

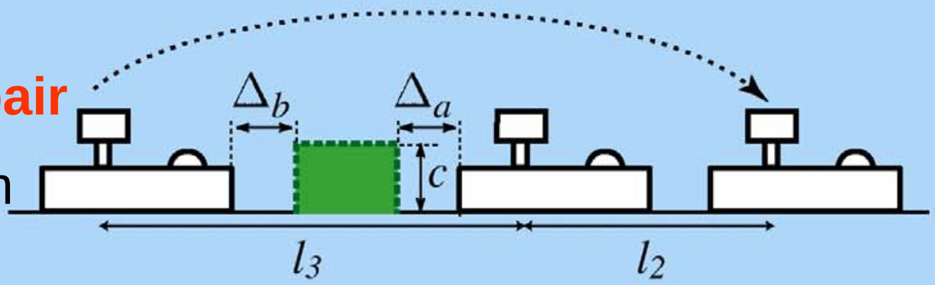
- ➢ **6-phase** optimal control problem

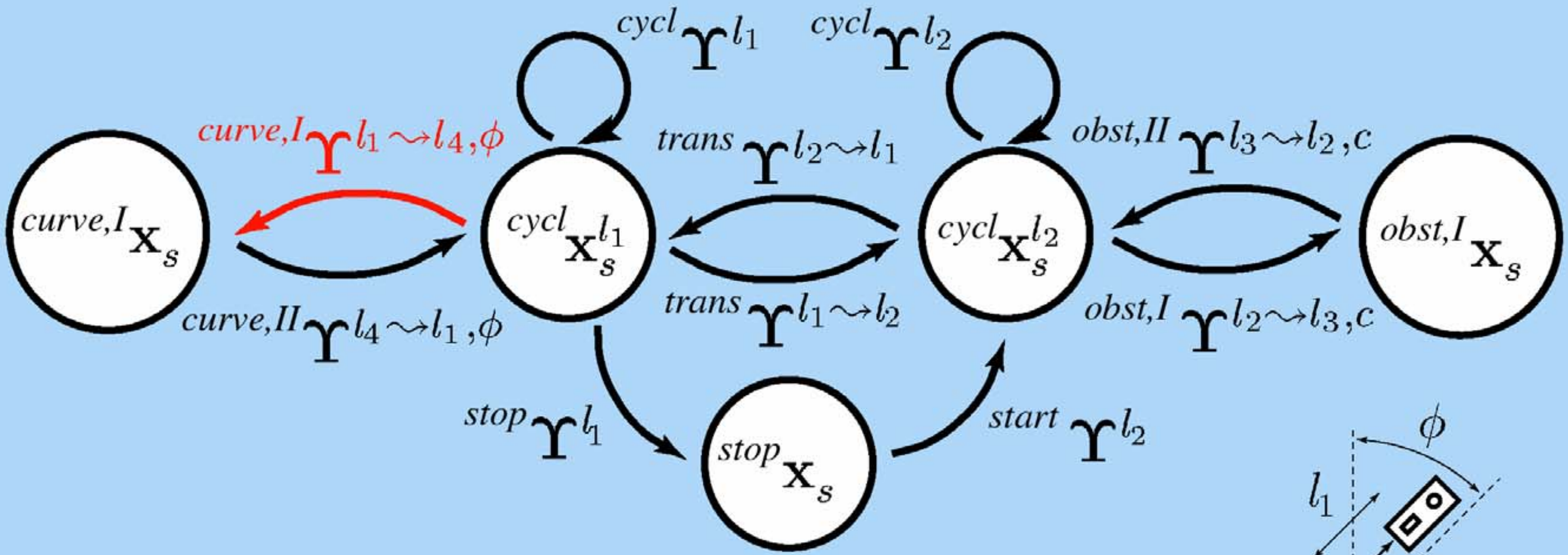


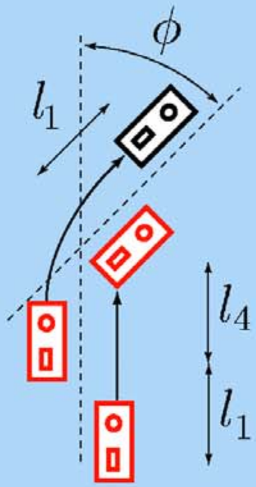


(6') Synthesize **obstacle primitive pair**

- ➢ **6-phase** optimal control problem

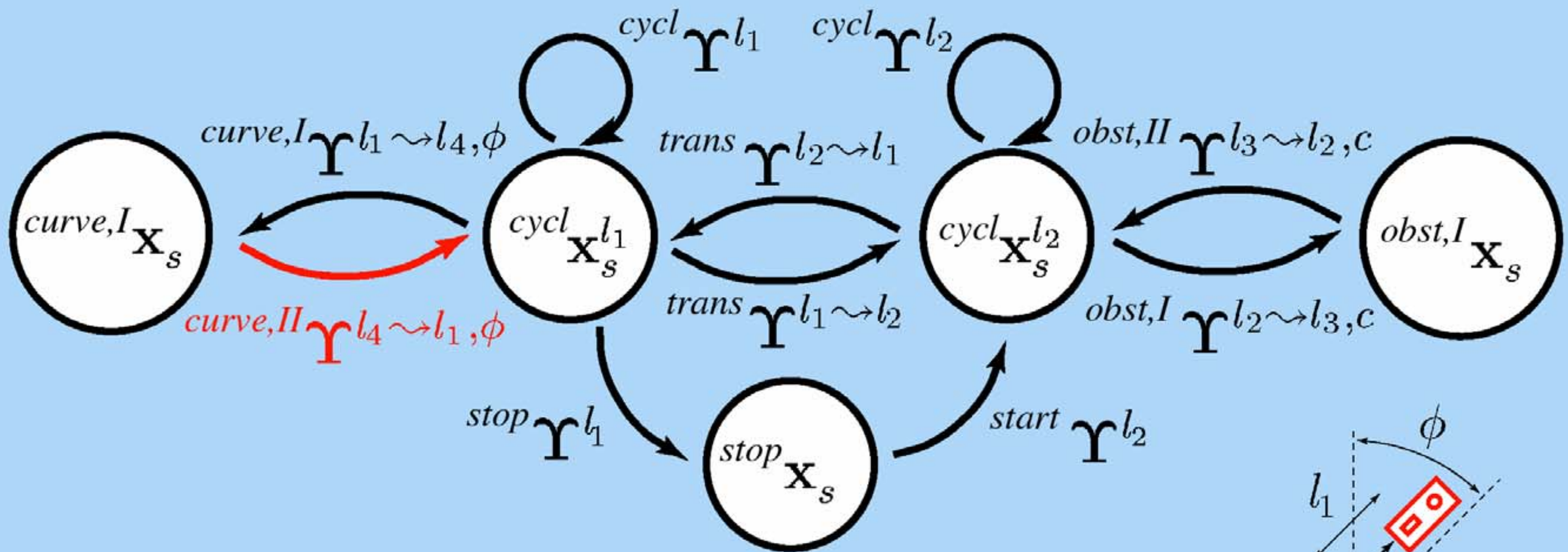


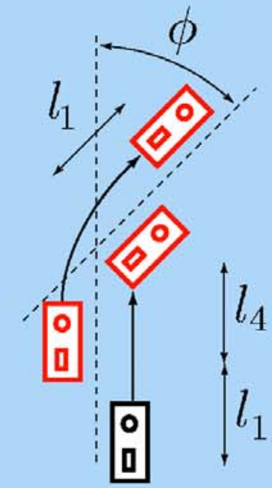




(7) Synthesize **curve primitive pair**

- ➢ **6-phase** optimal control problem

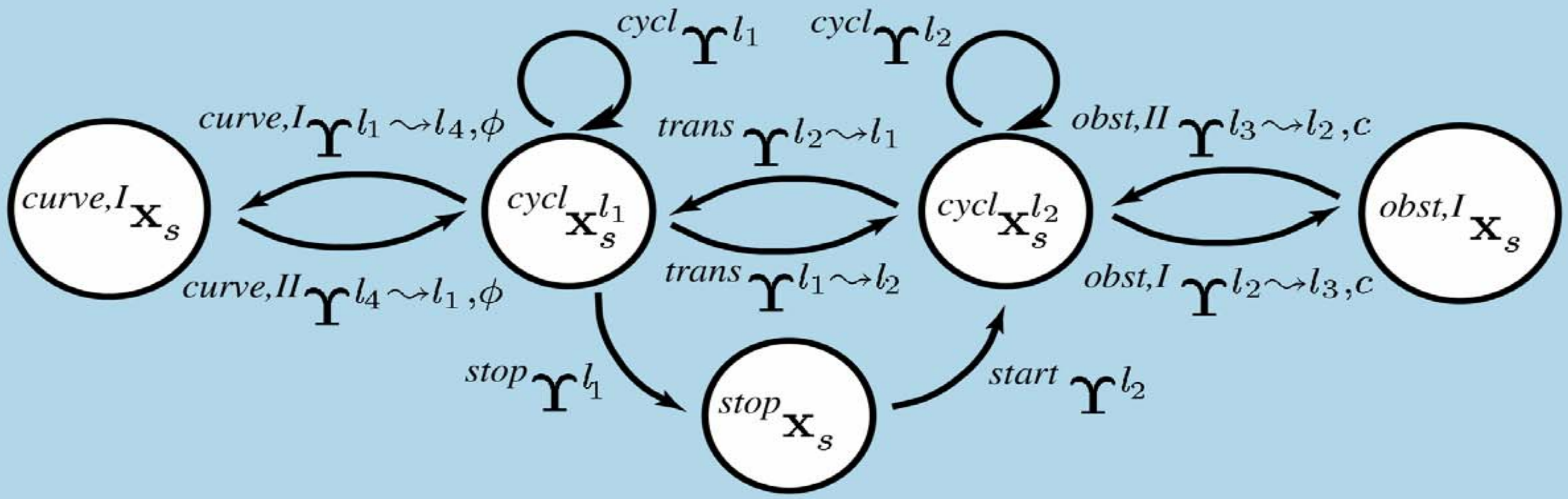




(7’) Synthesize **curve primitive pair**

- **6-phase** optimal control problem

Final Database = Knowledge Base
Comprising Available Walking Behaviours

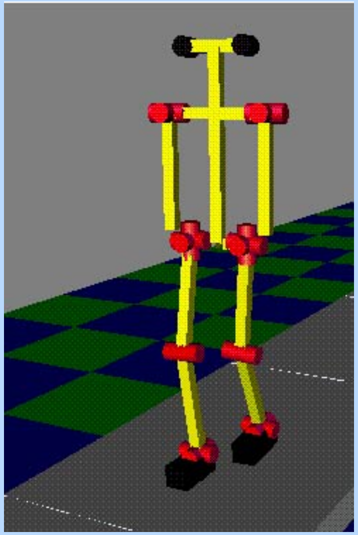


→ **Synthesis procedure emulates**

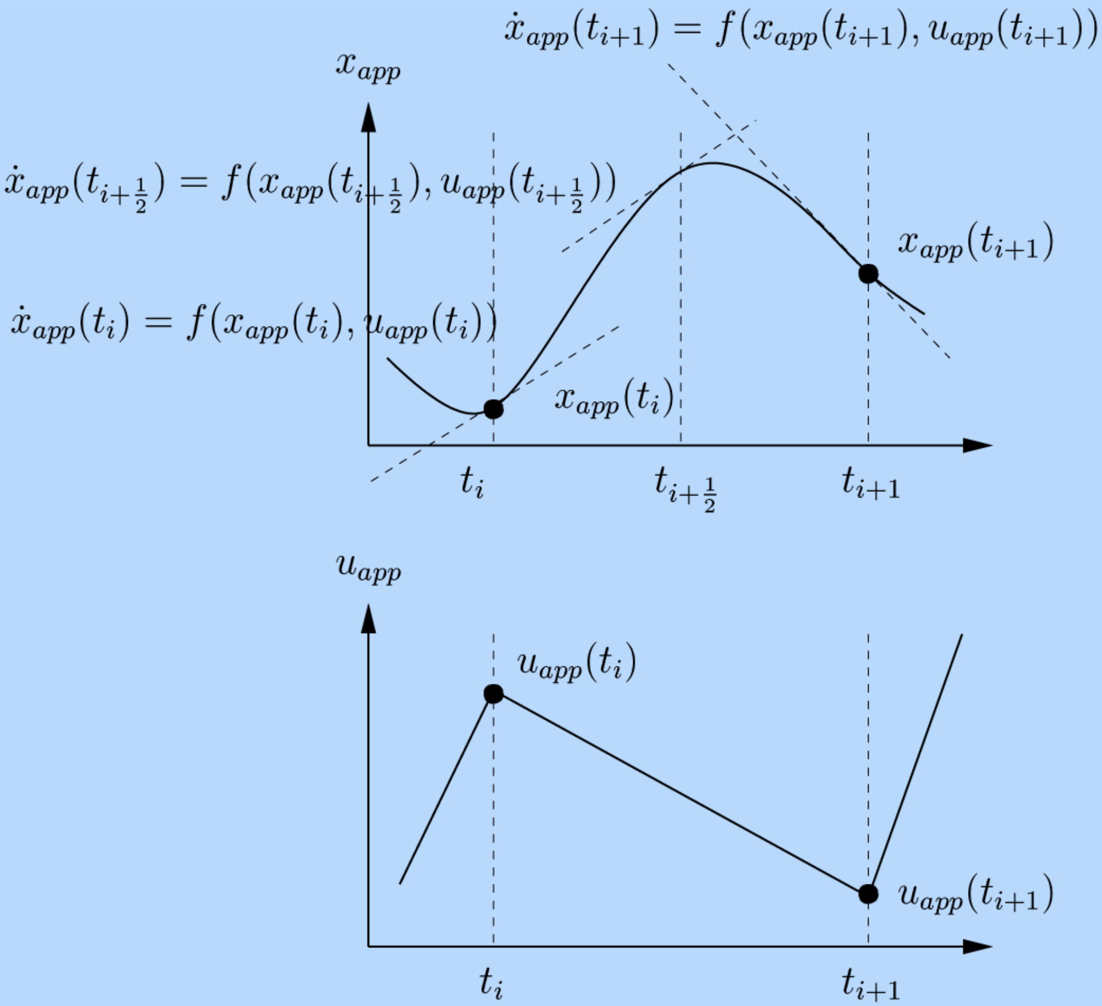
"*learning of elementary human walking behaviours by trial and error*"

Details of Numerical Database Generation

- **kinetic model of biped *Johnnie*** 6 joints / leg
- various **performance functions**
- numerical solution by **direct collocation**:
  continuous problem $\rightarrow$ time-discrete problem
- starting with feasible initial solution:
  automatic generation of primitives for straight-ahead walking with step-lengths 0.22, 0.26, ... 0.54 m (9 cyclic and 72 transition primitives)
- **typical computation time:** 0.5 - 1.0 hour / WP
- **total**: ca 700 WPs for *JOHNNIE*
- parameters:
  - average velocity: 0.5 $\mathrm{m/s}$
  - $t_s = 1.15$ s
  - fixed ratio t_1 / t_s: ~ 9 %
  - fixed ratio t_2 / t_s: ~ 83 %
  - step-width: $w = 0.20\ m$
  - friction coefficient: 0.7

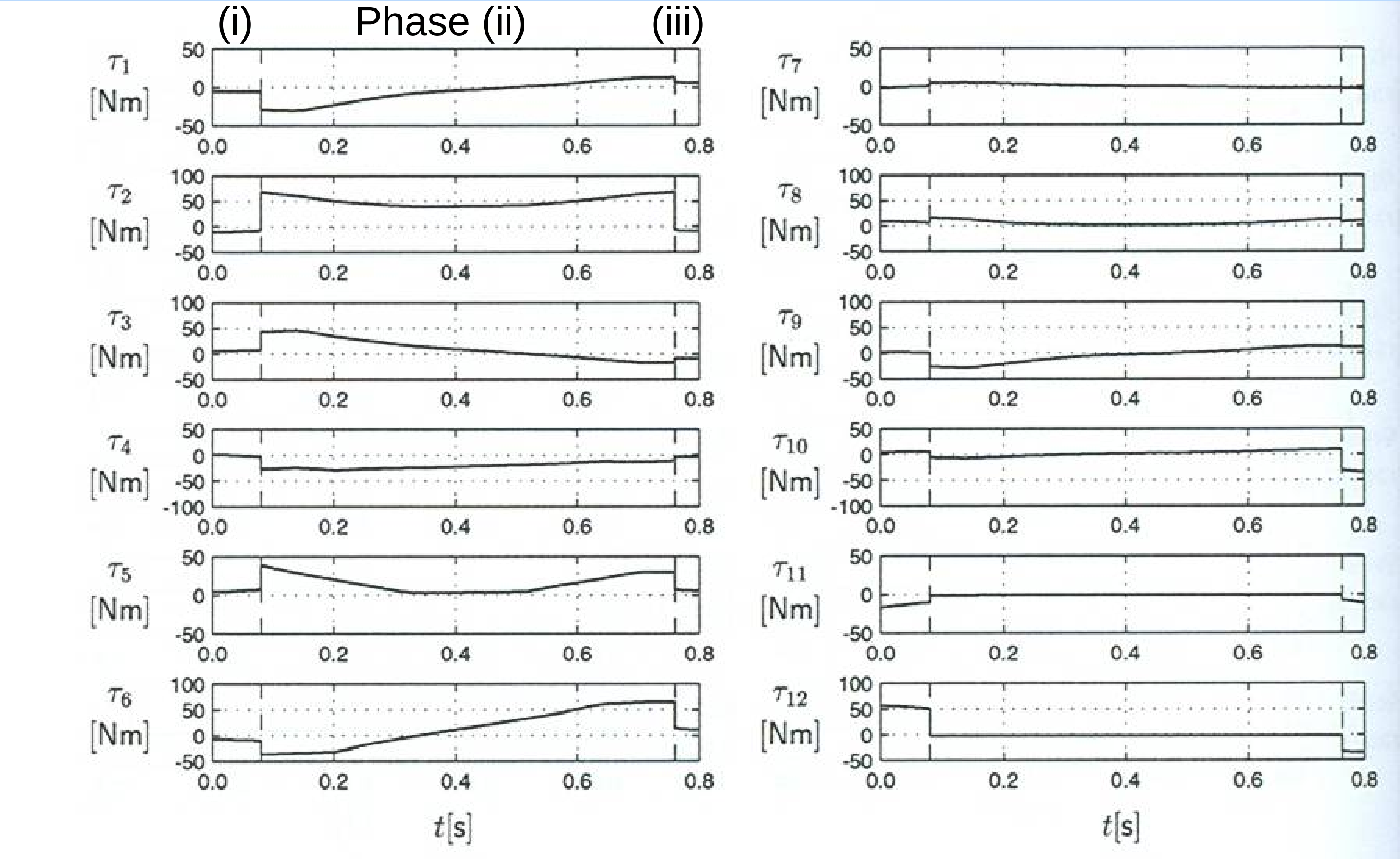


Direct Collocation (*DIRCOL*) Method

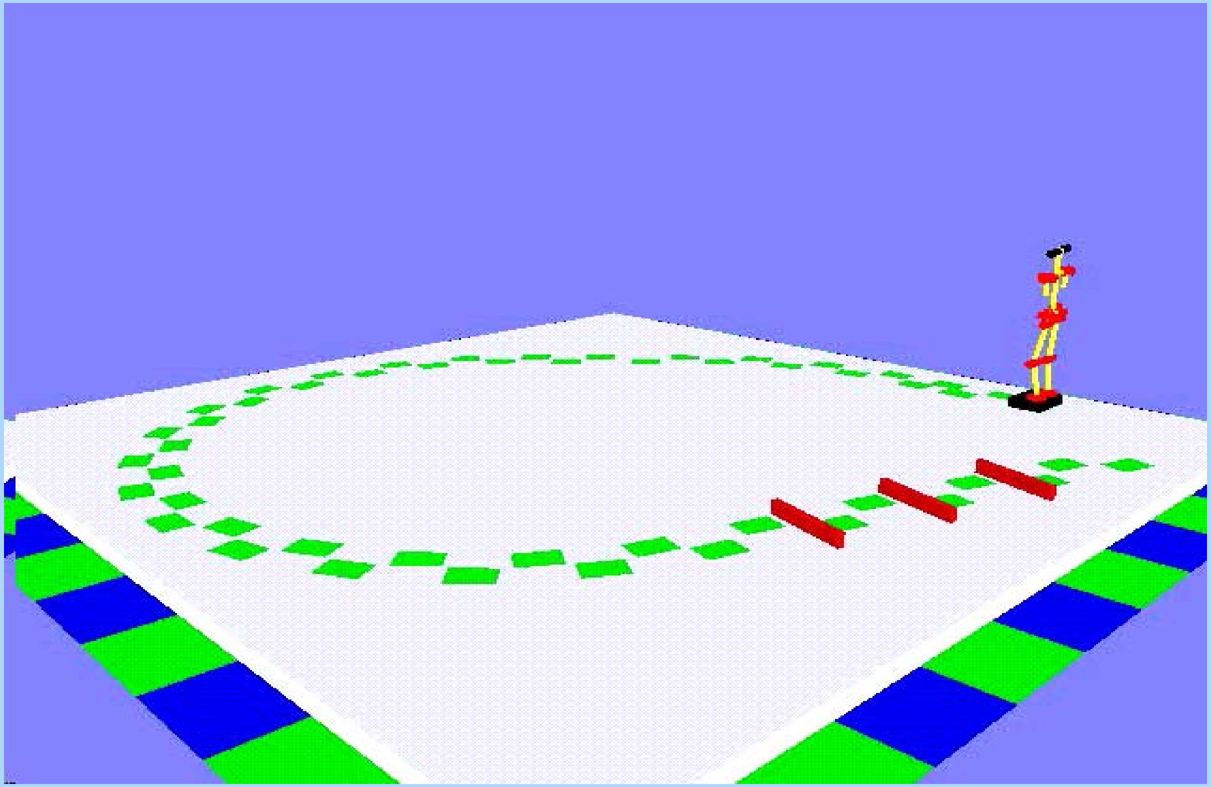


- time discretization
- approximation of *state trajectories* by cubic splines
- approximation of *controls* by piecewise linear functions
- collocation condition
- nonlinear programming problem (*SNOPT*)

Control Torques $\tau(t)$ for *Right Foot Forward*



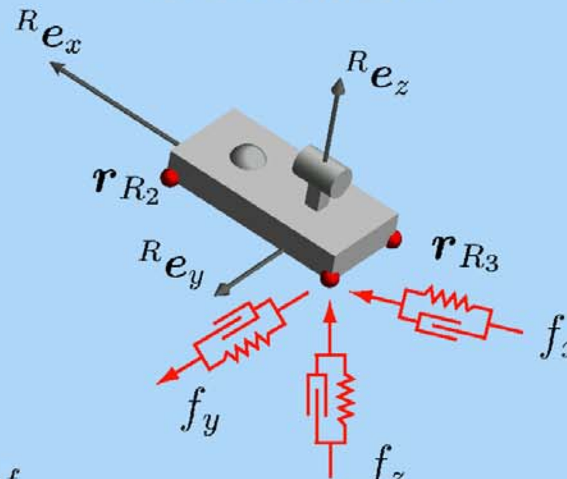
Biped Locomotion by Concatenation of Walking Primitives
with FF & PD - Joint - Control



Validation of sample walking patterns

$\boldsymbol{q}_{ref}(t), \boldsymbol{\tau}_{ref}(t)$

Spring-damper-contacts for simulation:



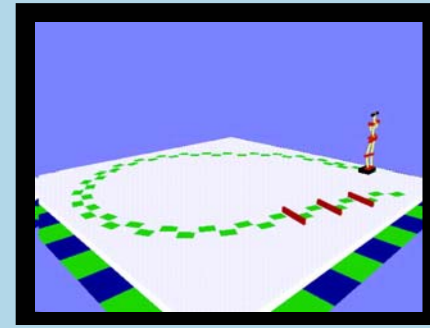
PD-Control Law: $\boldsymbol{\tau} = k_p(\boldsymbol{q}_{ref} - \boldsymbol{q}) + k_d(\dot{\boldsymbol{q}}_{ref} - \dot{\boldsymbol{q}}) + \boldsymbol{\tau}_{ref}$

Impact of Performance Functions

$$\phi^k = \sum_{i-1}^{N_j} |\dot{q}_i(t)\tau_i(t)|$$

Absolute mechanical power

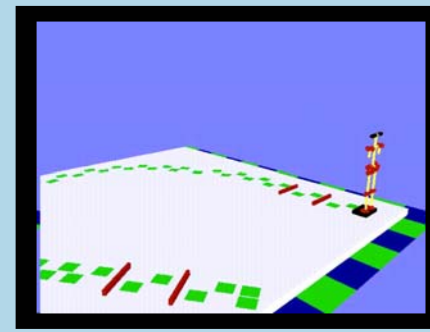
→ **"dynamic" gait**
high joint accelerations
during double support



$$\boxed{\phi^k = \sum_{i-1}^{N_j} (k_i\ddot{q}_i^2 + l_i\tau_i^2)}$$

Energy + acceleration

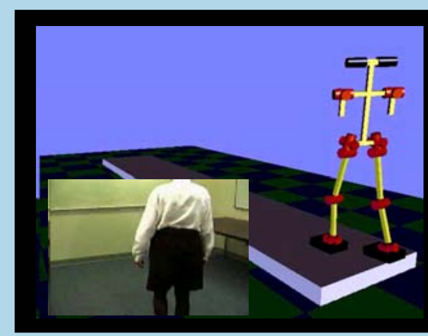
→ **"customized" gait**
reduced
joint accelerations



$$\phi^k = \sum_{i-1}^{N_j} \tau_i^2(t)$$

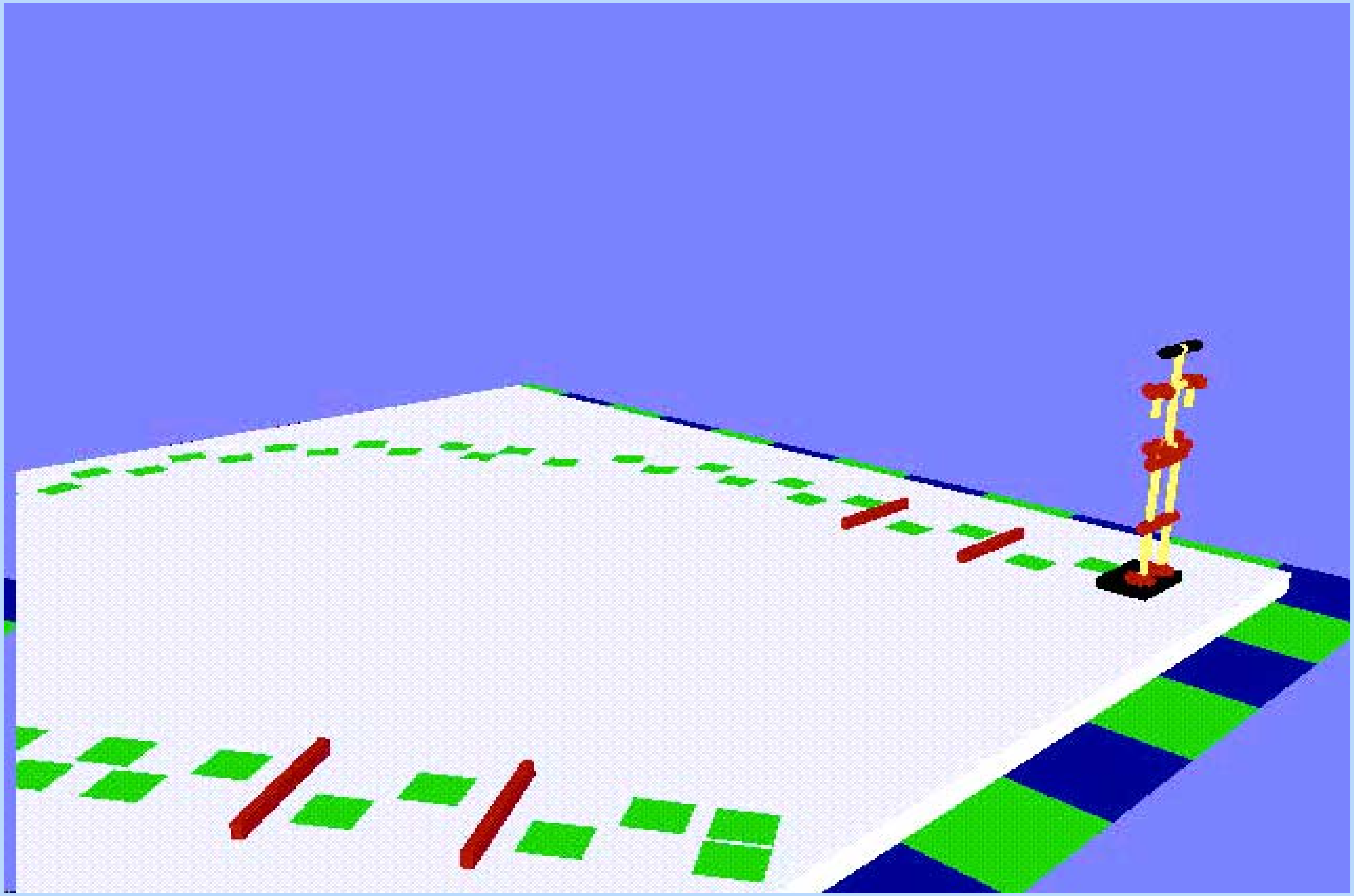
Energy

→ **"pathological" gait**
"gluteus medius limp"



Customized Gait

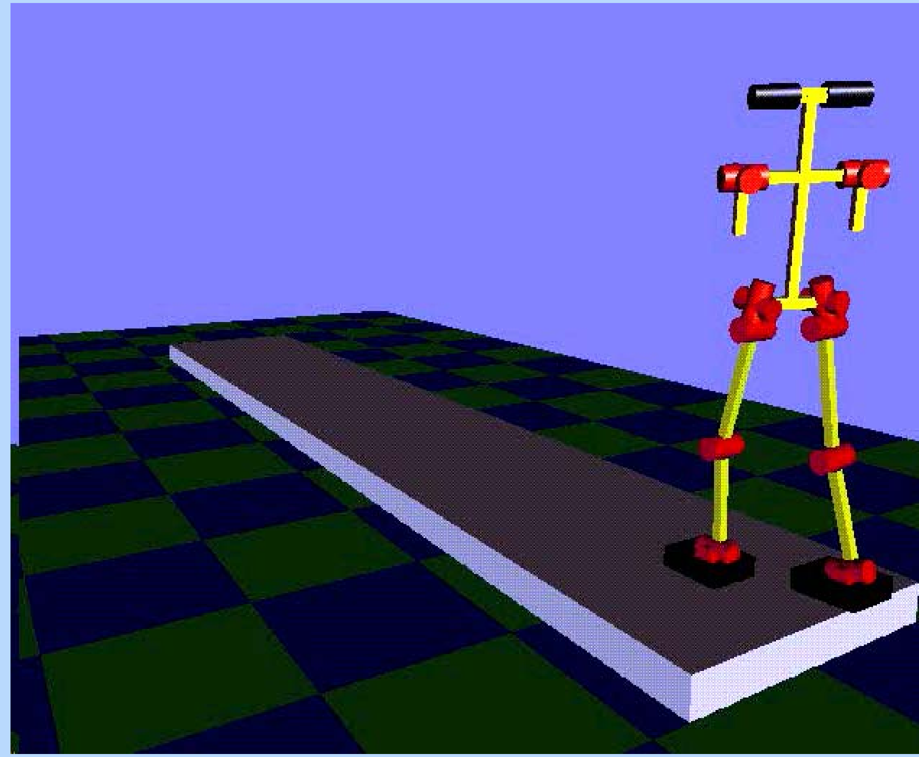
Min. Energy + Acceleration



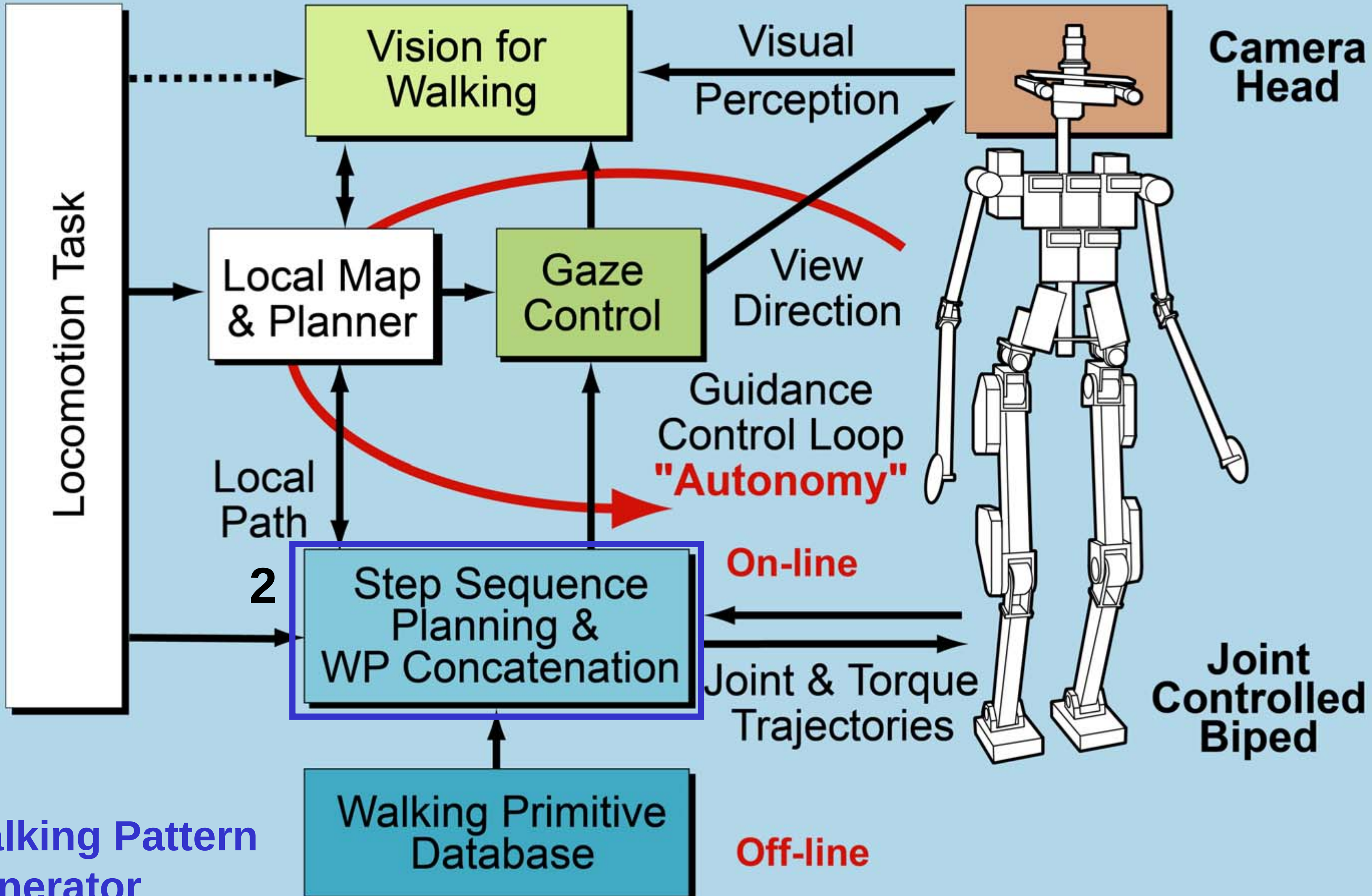
Pathological Gait

Min. Energy

"Patient with Gluteus Medius Limp"



$$\min_{\boldsymbol{\tau}(t)} \left[\int_0^{t_1} \sum_{i=1}^{N_j} \tau_i^2(t)dt + \int_{t_1}^{t_2} \sum_{i=1}^{N_j} \tau_i^2(t)dt + \int_{t_2}^{t_s} \sum_{i=1}^{N_j} \tau_i^2(t)dt \right]$$



Walking Pattern Generator

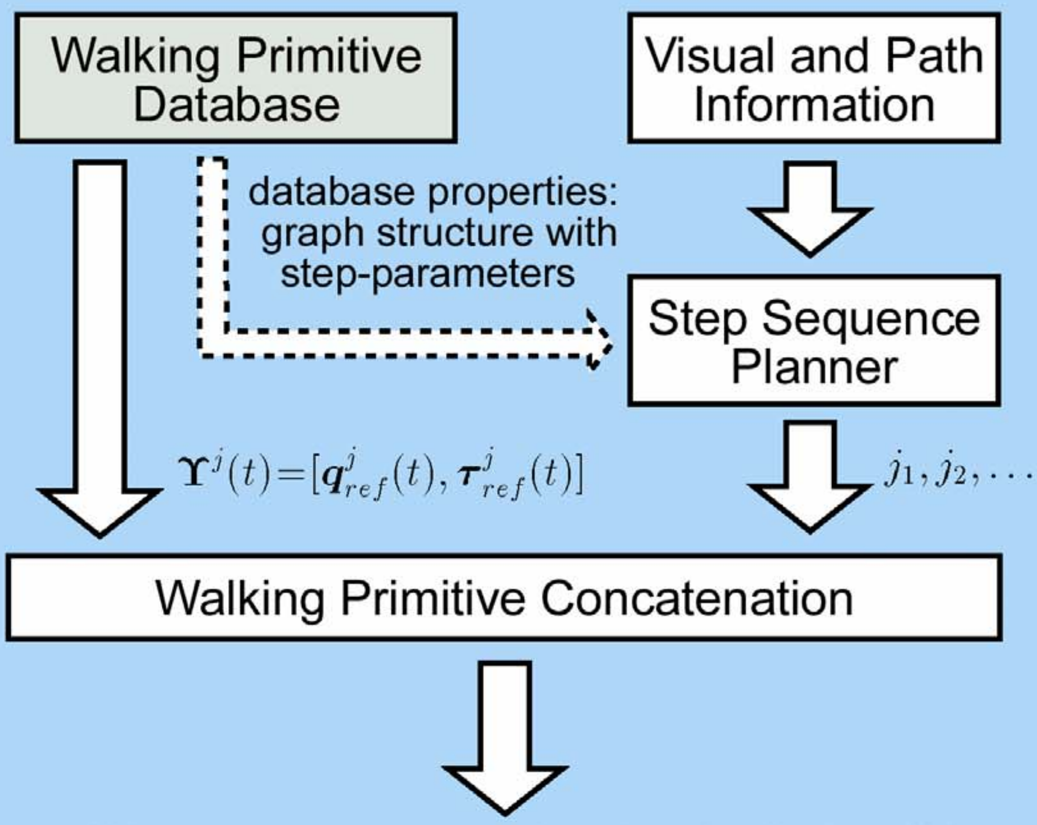
2

Situation-Dependent Concatenation of Walk Behaviours

Step Sequence Planning – online

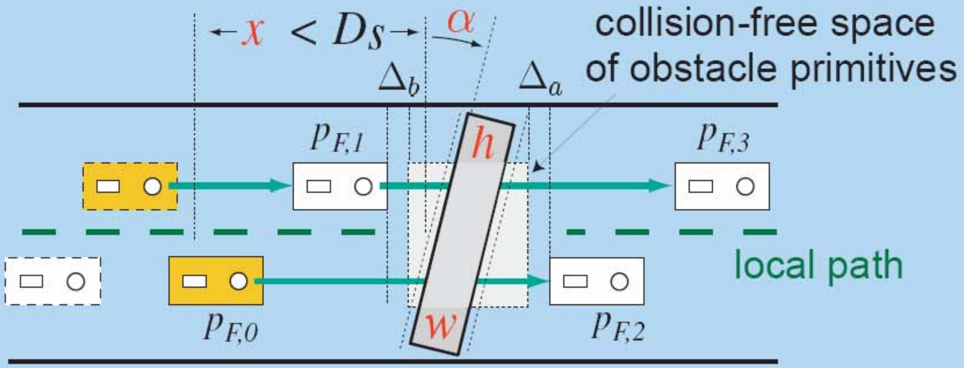
❖ *J. Denk, G. Schmidt*
Walking Primitive Database for Perception-based Guidance Control of Biped Robots,
European Journal of Control, Special Issue ECC'07, pp.171 - 188

Vision-based Walking Primitive Selection

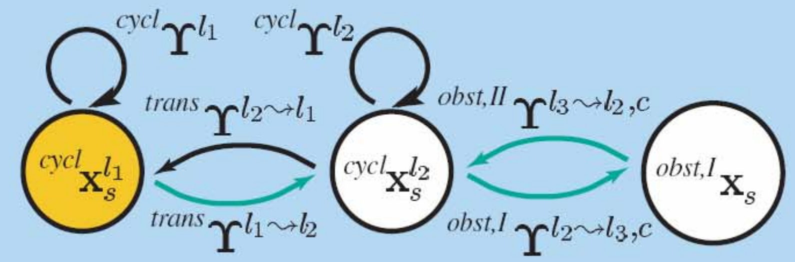


walking pattern: smooth, physically feasible joint trajectory $\boldsymbol{q}_{ref}(t)$ + control torques $\boldsymbol{\tau}_{ref}(t)$

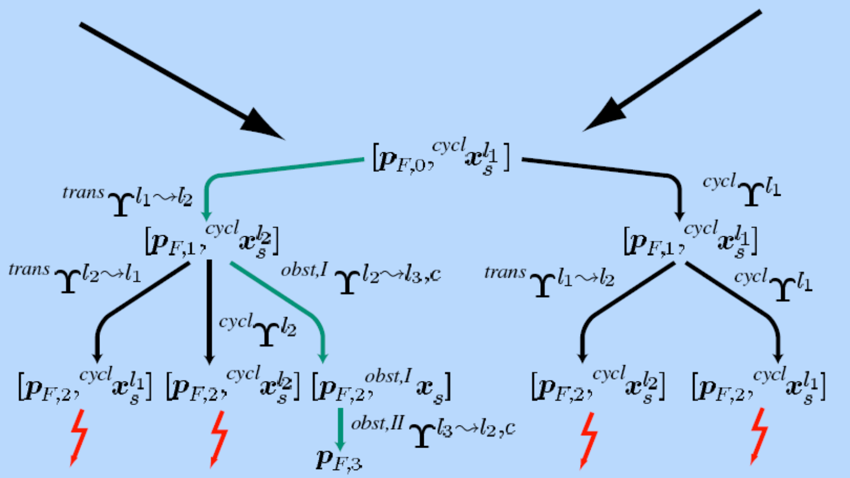
Step Sequence Planning by Tree Search



Situation in front of a barrier.
x, α, h, w provided by vision.

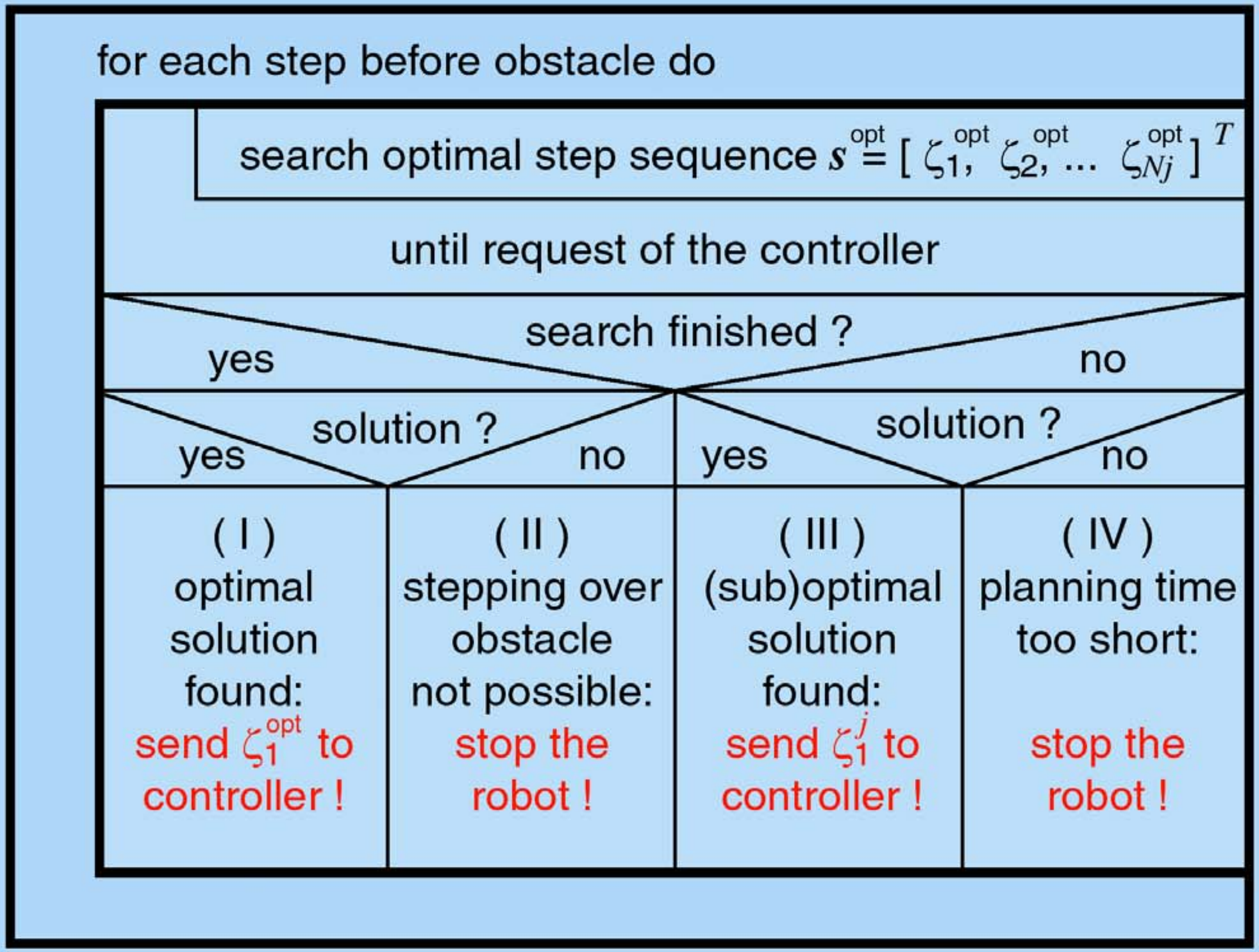


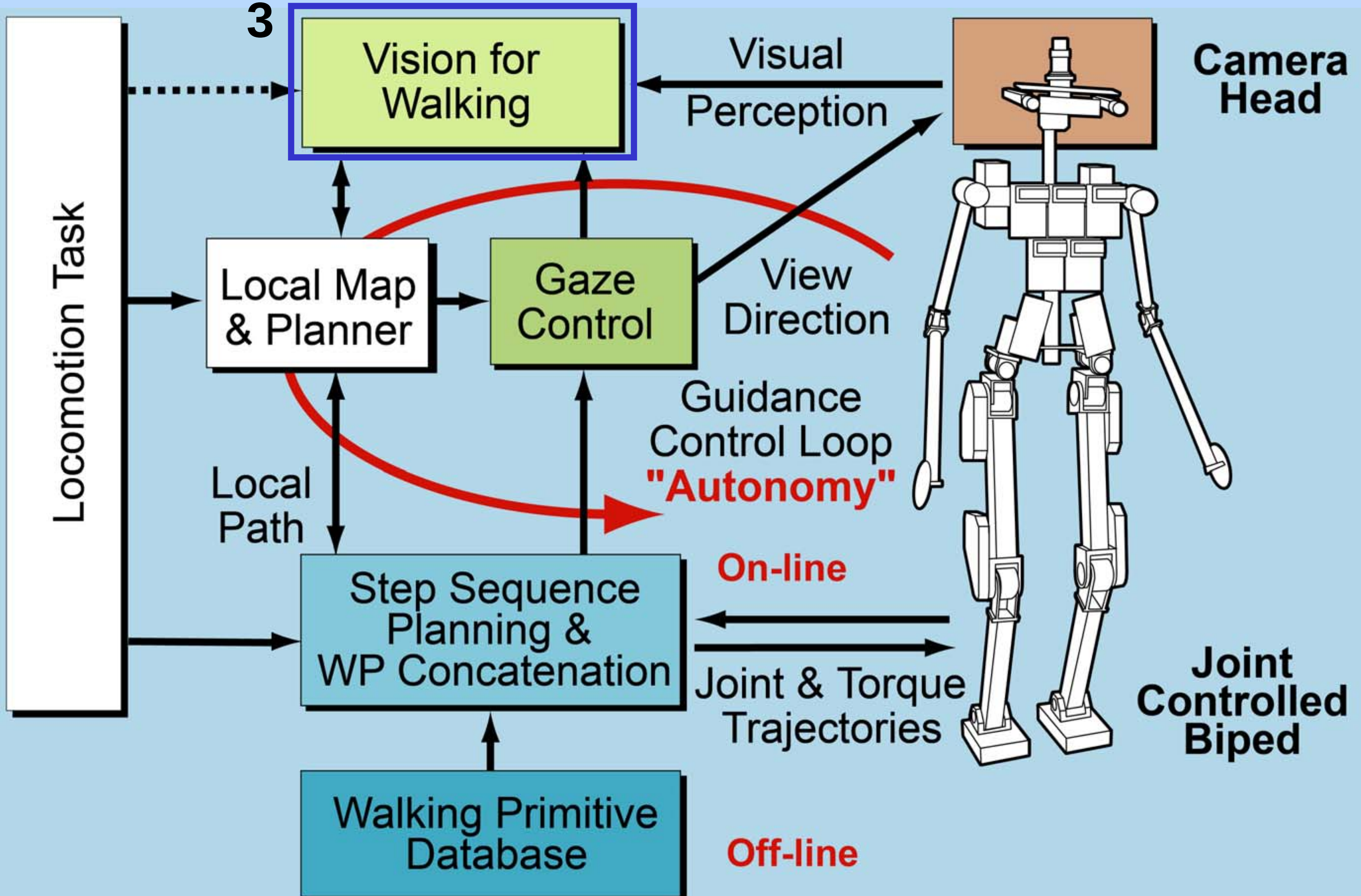
Walking primitive database



Search tree showing feasible step sequences

Reactive Behaviour
by Step-wise Step-sequence Replanning



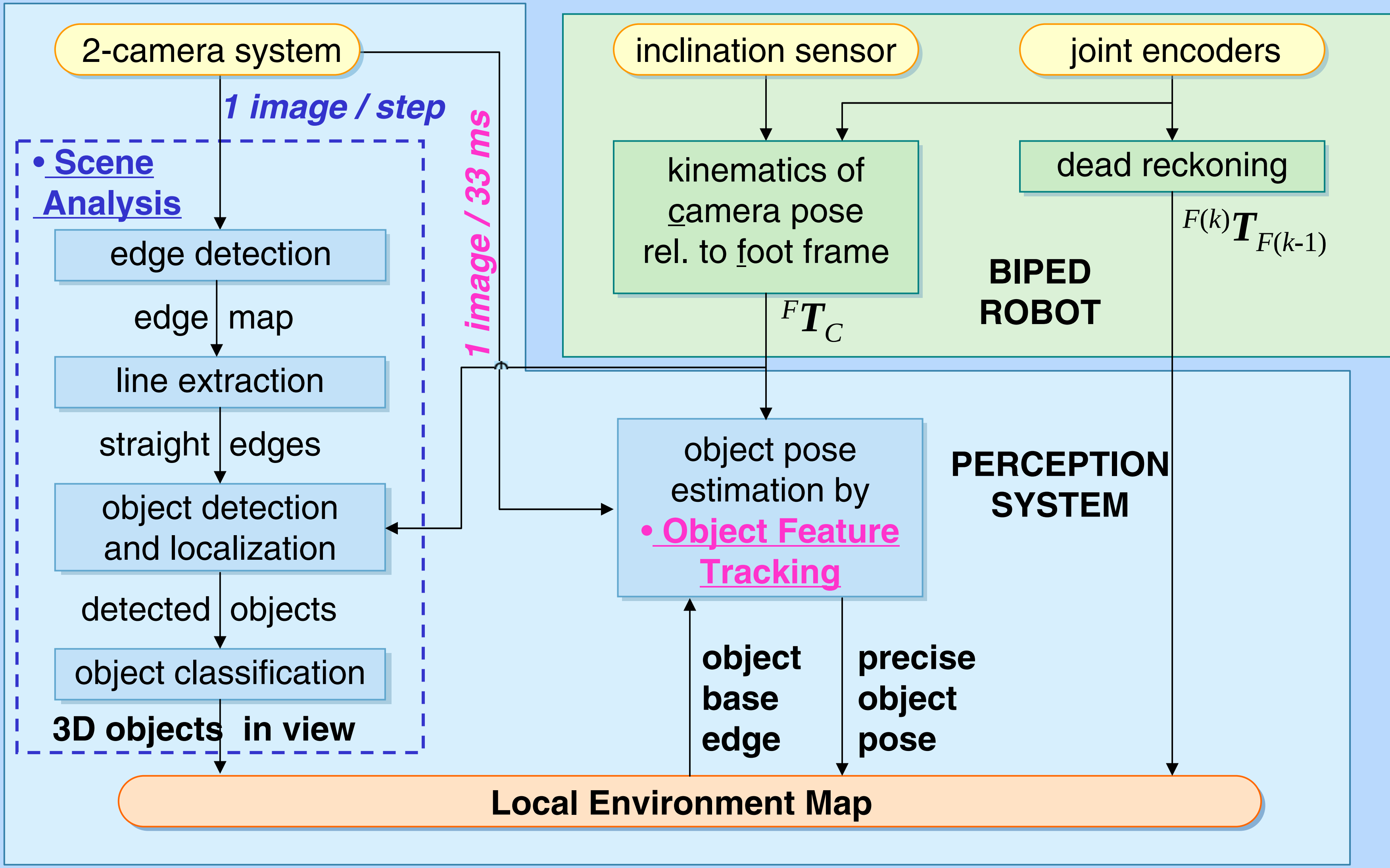

3
Vision for Walking
Visual Perception
Camera Head
Locomotion Task
Local Map & Planner
Gaze Control
View Direction
Guidance Control Loop
"Autonomy"
Local Path
Step Sequence Planning & WP Concatenation
On-line
Joint & Torque Trajectories
Joint Controlled Biped
Walking Primitive Database
Off-line

3

Vision for Walking

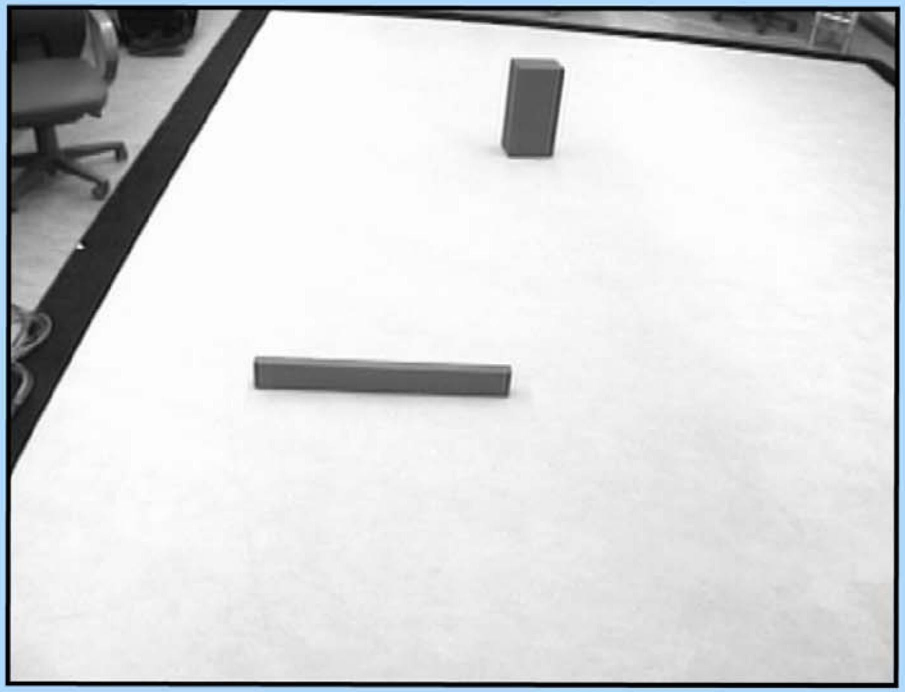
Perception + Map-based Approach

❖ *R. Cupec*
Scene Reconstruction and Free Space Representation
for Biped Walking Robots,
Doctoral Dissertation, TU München, 2005

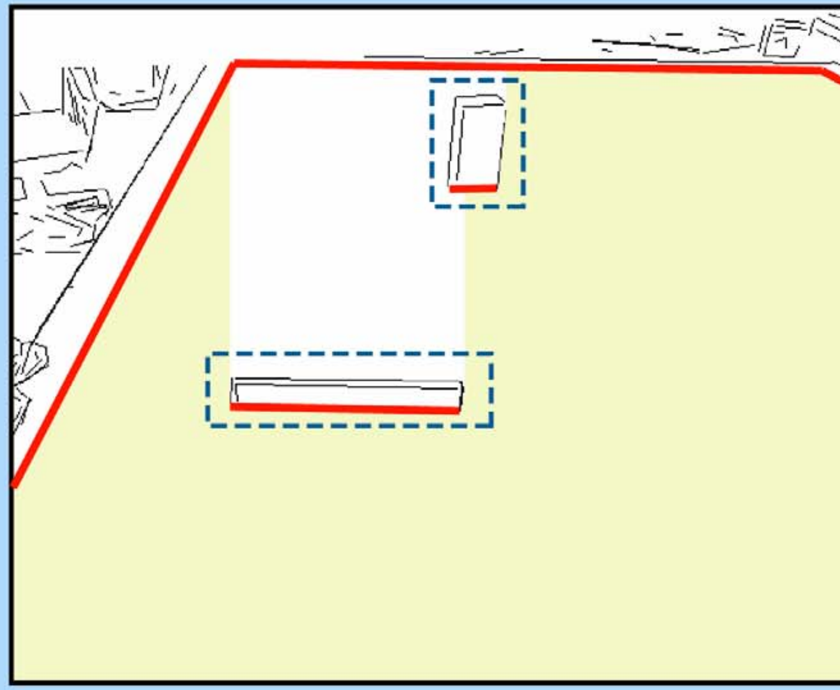


Architecture of Perception and Data Fusion System

Scene Analysis and Feature Tracking, Free Space Detection, Object Classification & Localization



left camera image

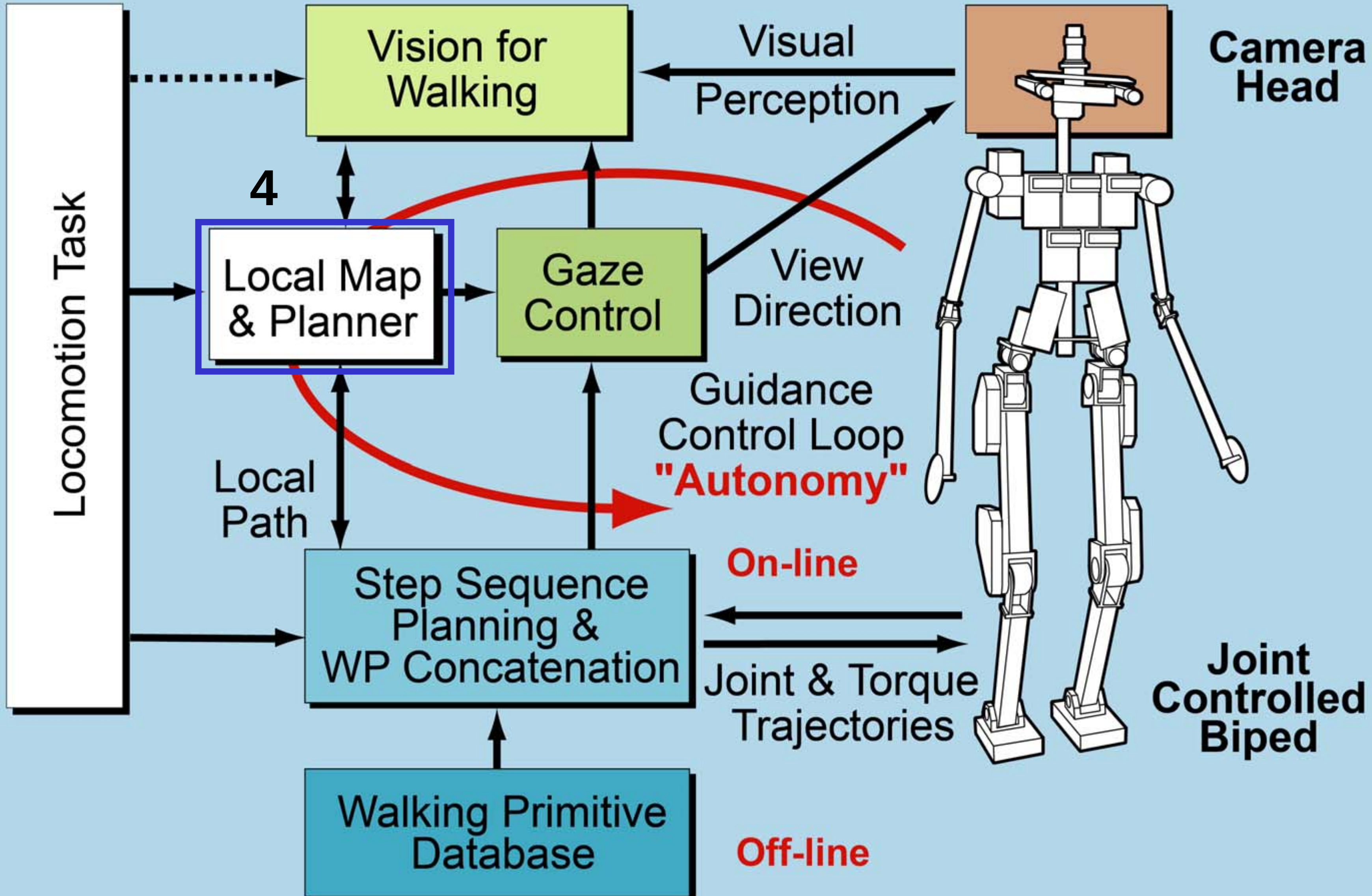


detected lines

base edges

obstacles

obstacle free area ahead of the next obstacles


Locomotion Task
Vision for Walking
Visual Perception
Camera Head
4
Local Map & Planner
Gaze Control
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Joint Controlled Biped
Walking Primitive Database
Off-line

4

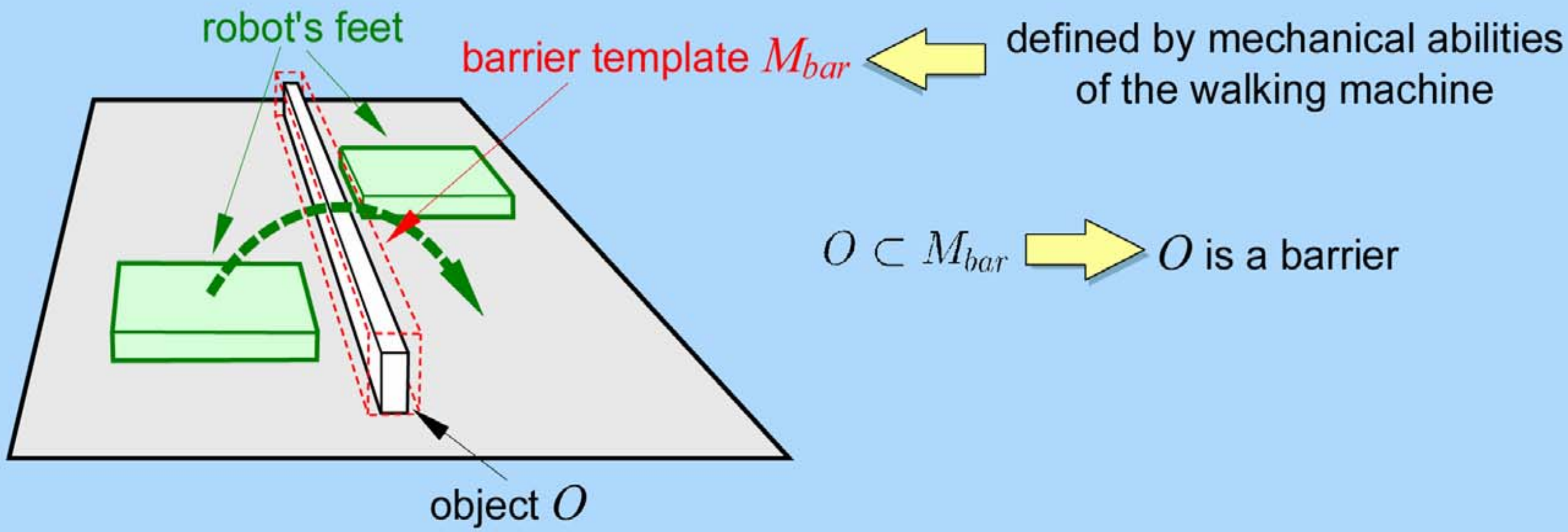
Map-based 3-D Path Planning for Next Locomotion Action

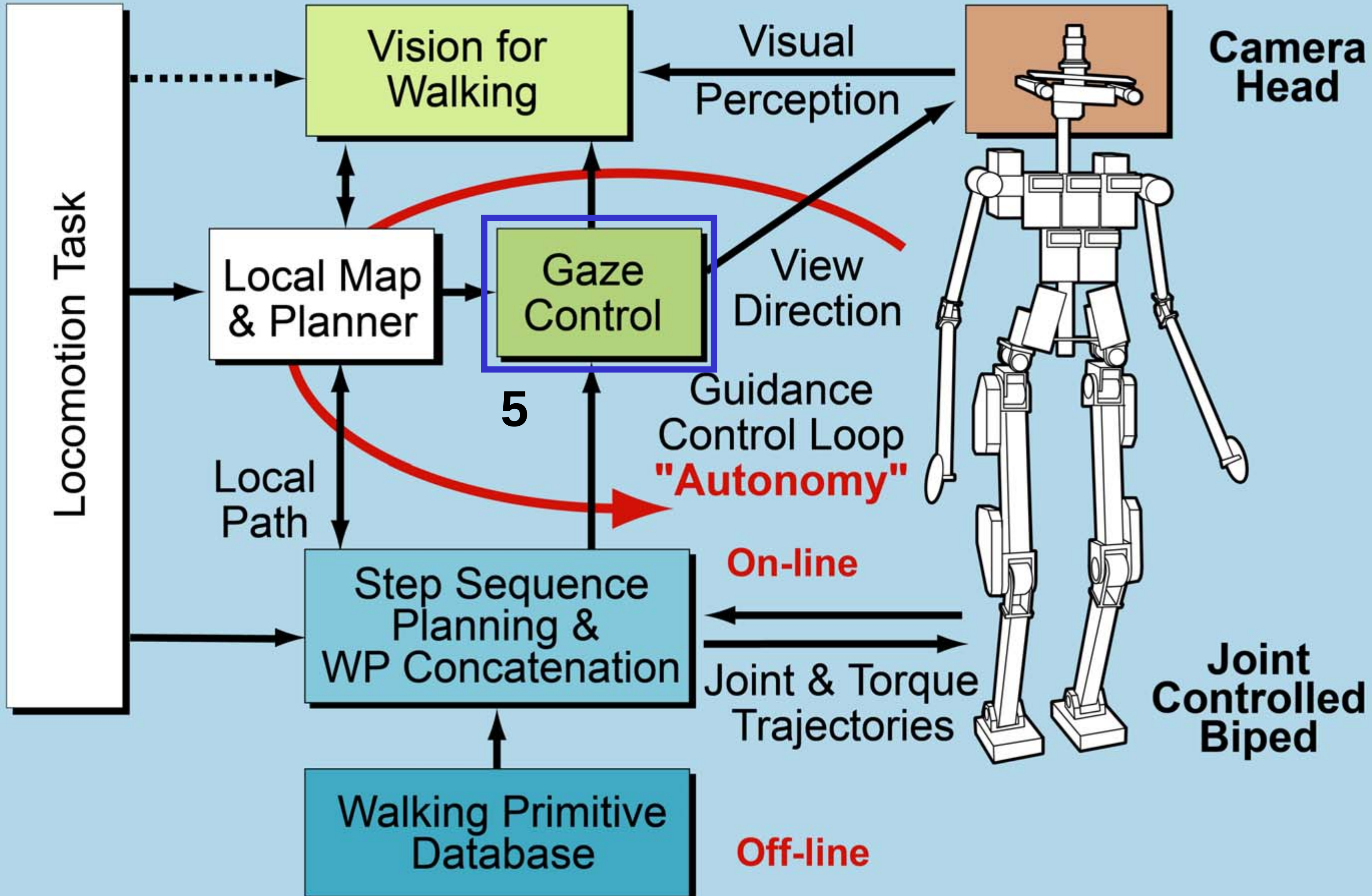
❖ *R. Cupec, G. Schmidt*
An Approach to Environment Modelling for Biped Walking Robots,
Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems,
IROS 2005, pp. 2089 - 3094.

Local 3-D Path
Suitable for Current Obstacle Situation

3 Classes of Cuboid Obstacles

- **stair**: robot can step **on** it
- **barrier**: robot can step **over** it
- **wall:** robot can **go around** or **stops**




Vision for Walking
Visual
Perception
Camera Head
Locomotion Task
Local Map & Planner
Gaze Control
View Direction
5
Guidance Control Loop
"Autonomy"
Local Path
Step Sequence Planning & WP Concatenation
On-line
Joint & Torque Trajectories
Joint Controlled Biped
Walking Primitive Database
Off-line

5

Selection of Camera View Direction

Gaze Behaviours

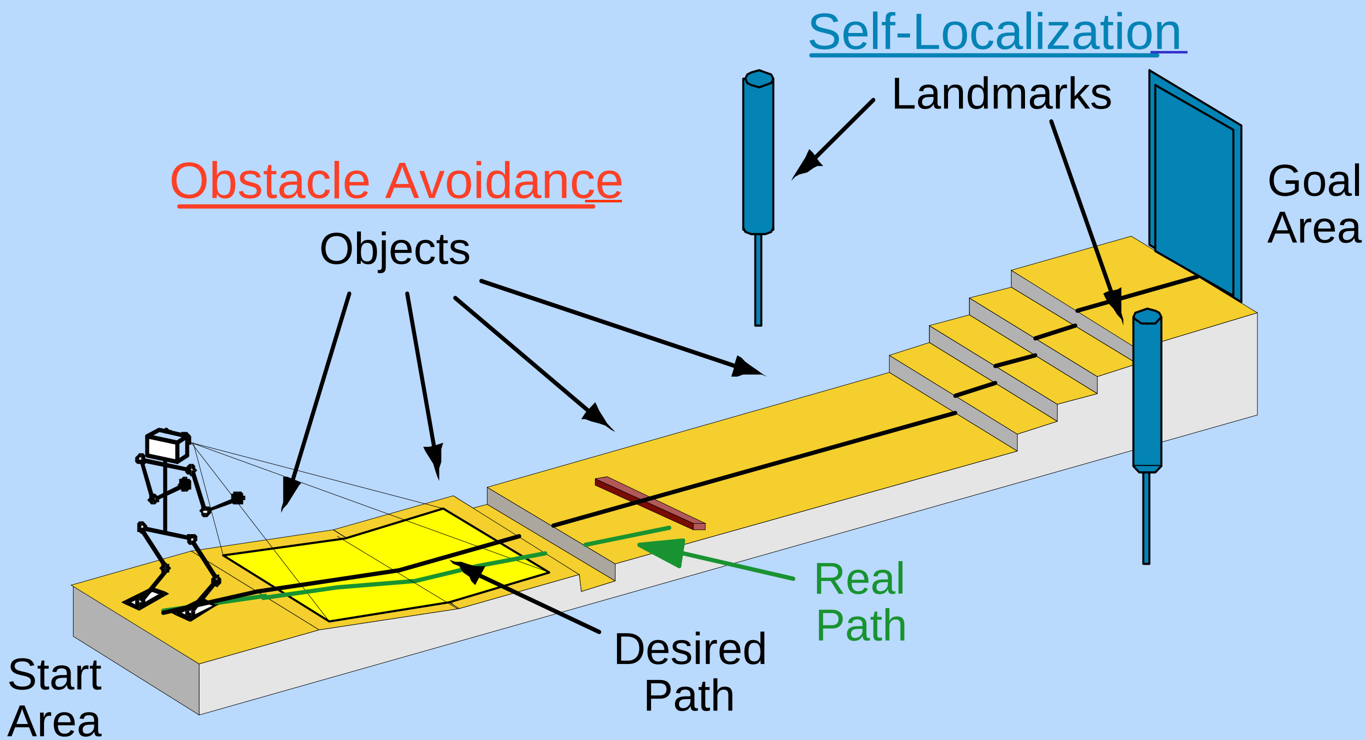
❖ *J.F. Seara, G. Schmidt*
Intelligent Gaze Control for Vision-guided Humanoid Walking: Methodological Aspects,
Robotics and Autonomous Systems, Vol. 48, 2004, pp. 338--342.

❖ *J.F. Seara, K.H. Strobl, G. Schmidt*
Path-dependent Gaze Control for Obstacle Avoidance in Vision-guided Humanoid Walking
Proc. IEEE Int. Conf. on Robotics and Automation, ICRA 2003, pp. 887—892.

Intention Problem: *"Where and how to look next ?"*

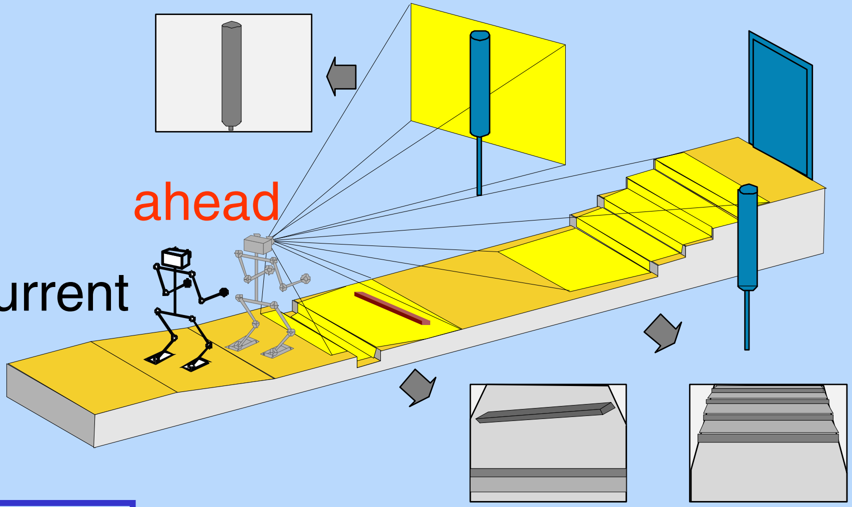
Cameras:
- Limited Field of View
- Active Vision System

⇒ Adaptation of View Direction, i.e. pan, tilt



Bio-inspired "1-Step-Ahead" Gaze Control Strategy

Maximization of anticipated
visual information content
by selection of proper camera
orientation $\Omega = $ (*pan, tilt*)



$$\widehat{\boldsymbol{\Omega}}_\star = \arg\max_{\widehat{\boldsymbol{\Omega}}} \sum_{i=1}^{N} \widehat{\mathcal{IC}}_i(\widehat{\boldsymbol{\Omega}}, {}_0\boldsymbol{x}_0, {}_F\boldsymbol{x}_i, \nu_i),$$

$$\widehat{\boldsymbol{\Omega}}_{min} \leq \widehat{\boldsymbol{\Omega}} \leq \widehat{\boldsymbol{\Omega}}_{max} \quad \text{and}$$

$$\boldsymbol{g}(\dot{\boldsymbol{\Omega}}) = \boldsymbol{0},$$

Information Content $\mathcal{IC}$
Maximization
$\Downarrow$
Uncertainty
Minimization

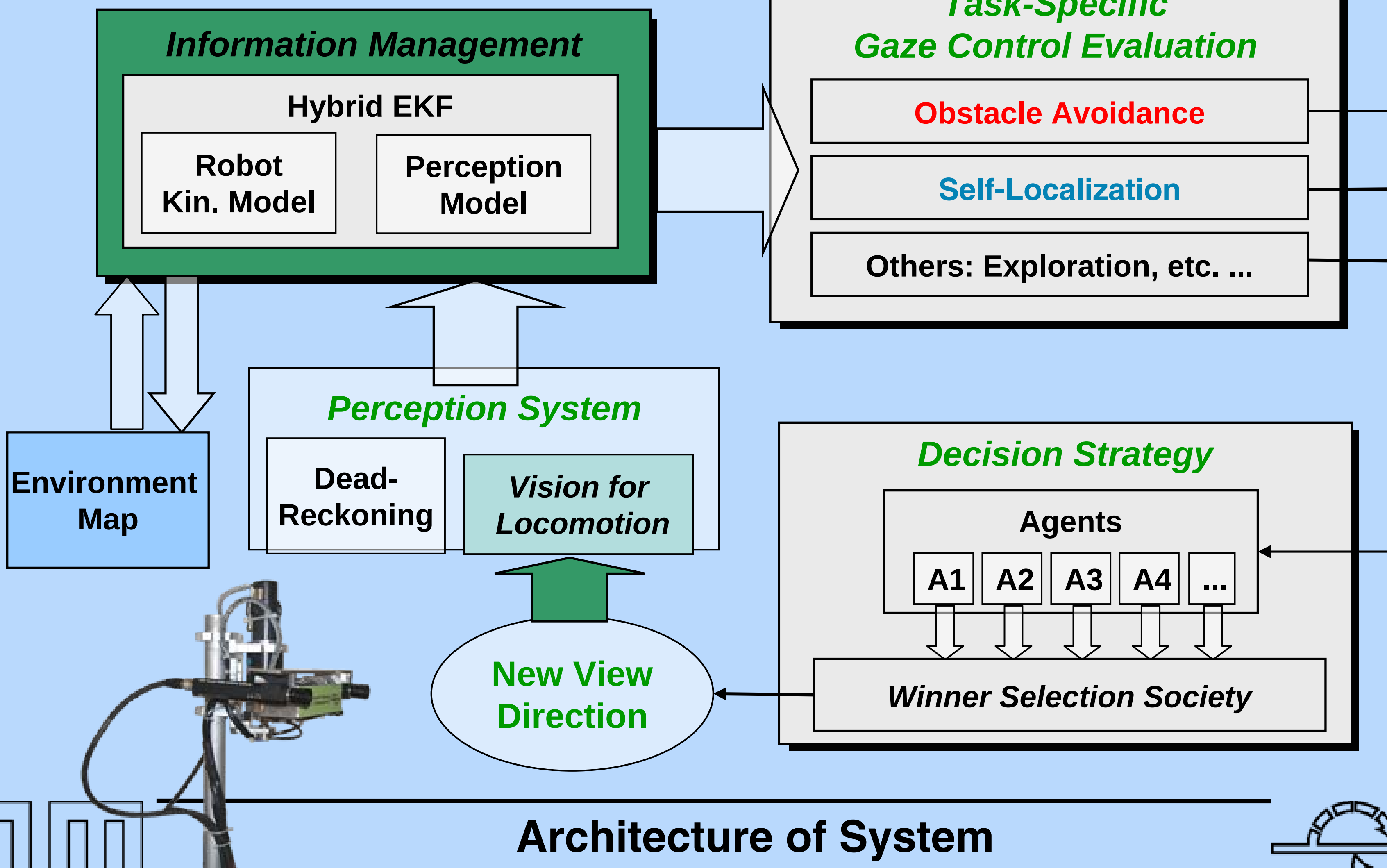
$$
\begin{aligned}
\boldsymbol{x}_{k+1} &= \boldsymbol{f}(\boldsymbol{x}_k, \boldsymbol{u}_{k+1}, \boldsymbol{w}_k) \\
&= \boldsymbol{x}_k(1-\gamma_{k+1}) + \boldsymbol{f}_S(\boldsymbol{x}_k, \boldsymbol{u}_{k+1}, \boldsymbol{w}_k)\gamma_{k+1}
\end{aligned}
$$

$\gamma_k = 1:$ change of S_F

$\gamma_k = 0:$ no change of S_F

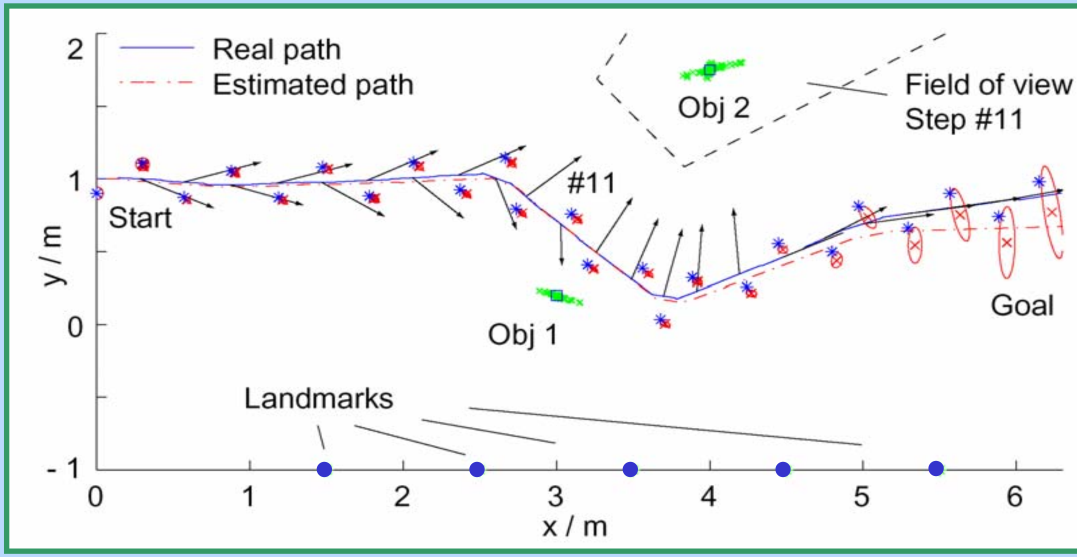
- **Hybrid Extended Kalman Filter Approach**

S_F: foot frame

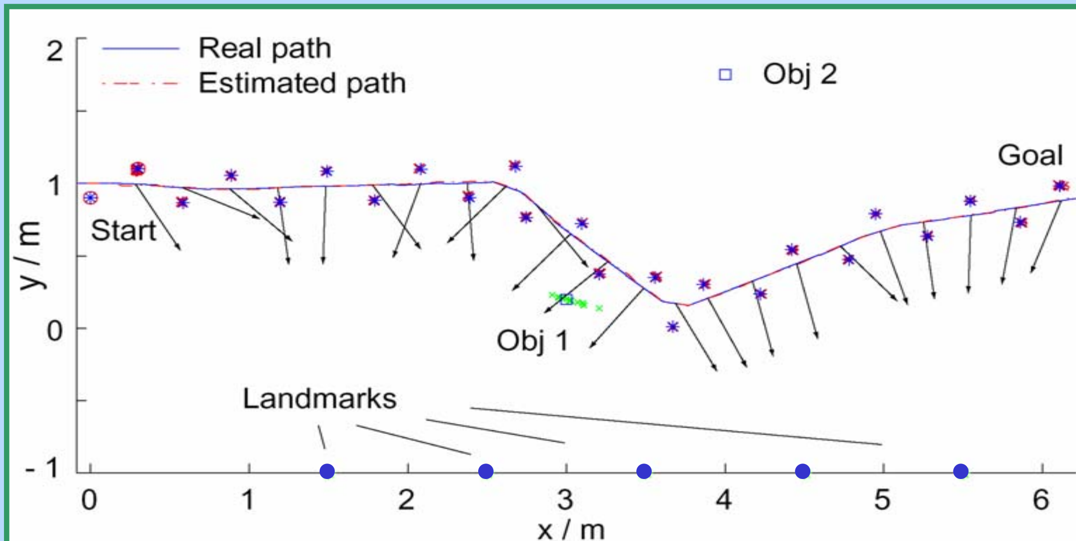


Architecture of System for *Task- and Situation*-dependent Gaze Selection

Task-Specific Gaze Control:



Obstacle Avoidance only



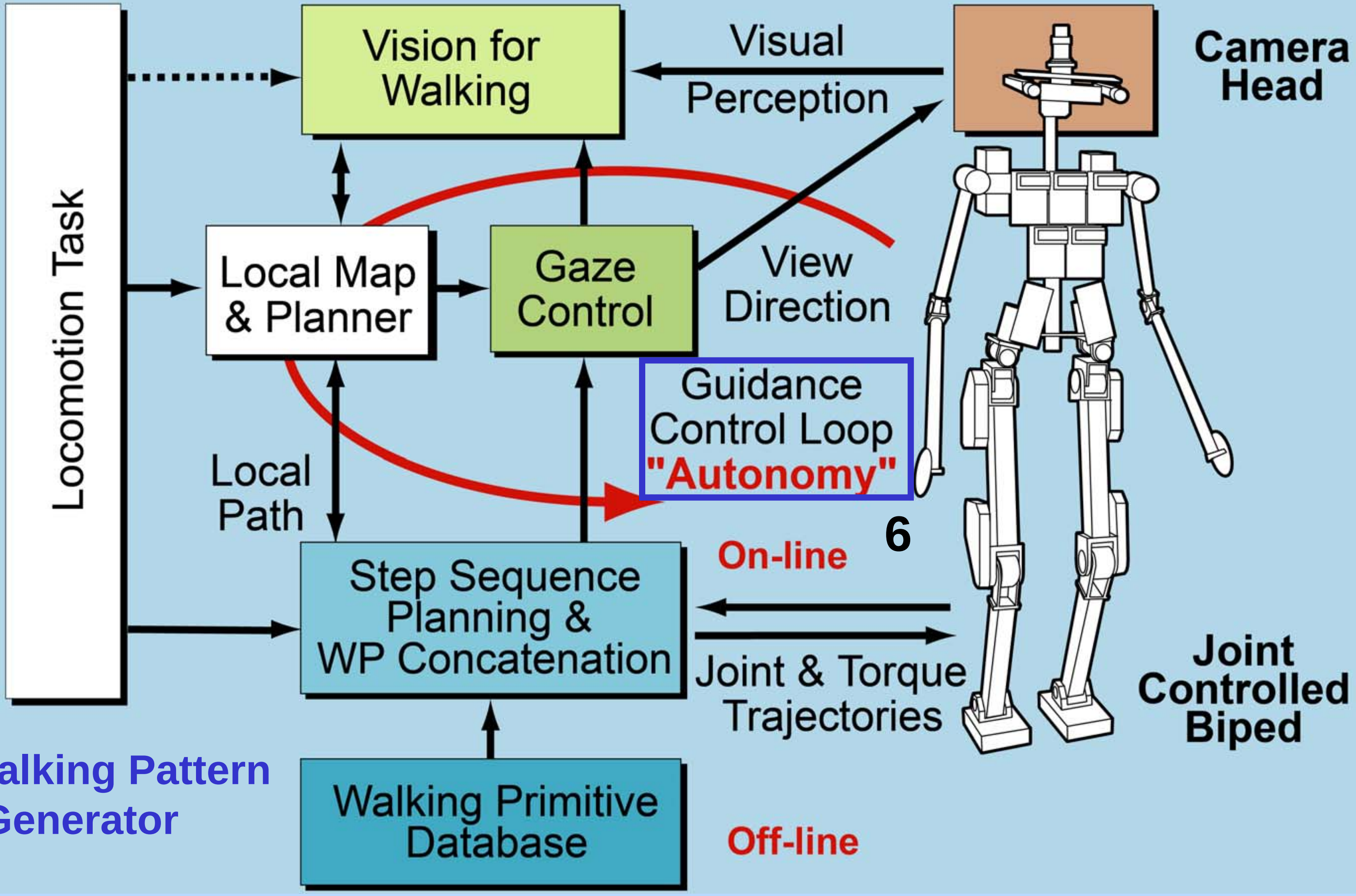
Self-Localization only

$(x_S, y_S, \theta_S) = (0.3\text{ m}, 0.2\text{ m}, 0°)$

$(\sigma_x, \sigma_y, \sigma_\theta) = (0.005\text{ m}, 0.005\text{ m}, 3°)$

14 measurements per step

Results from Simulation Studies



Walking Pattern Generator

6

Locomotion Autonomy by means of Perception-based Application of Behaviours

= Intelligent Walking

❖ *R. Cupec, O. Lorch, G. Schmidt*
Vision-guided Humanoid Walking – Concepts and Experiments, Proc. 18th Workshop on Autonomous Mobile Systems, AMS 2003, Springer Verlag, pp. 1 - 11

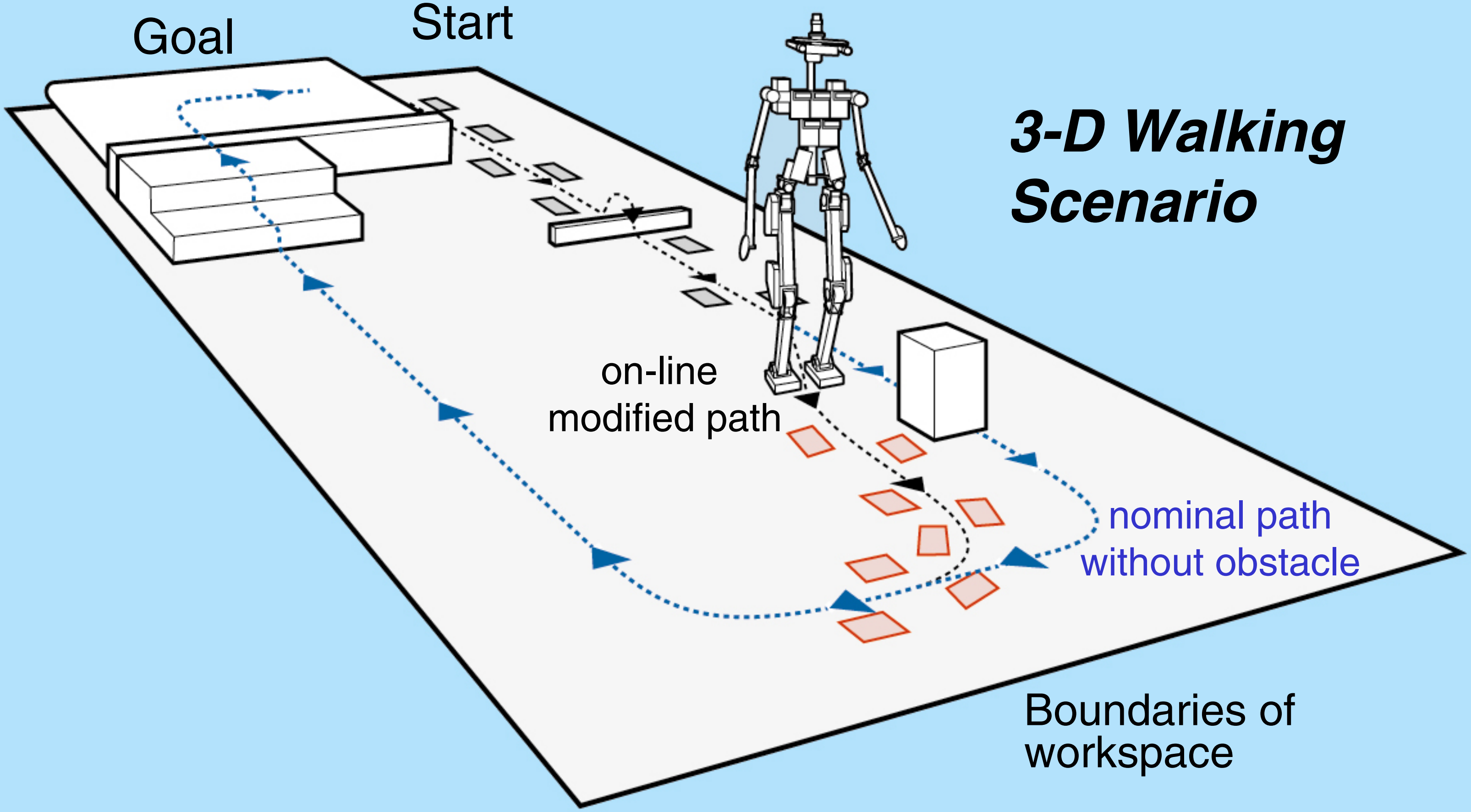
❖ *R. Cupec, G. Schmidt , O. Lorch*
Experiments in Vision-Guided Robot Walking in a Structured Scenario, Proc. of IEEE Int. Symp. on Industrial Electronics, ISIE 2005, pp. 1 - 6

Experimental Platform #3

- Visual Guidance System and Pan-Tilt Stereo Head, Institute of Automatic Control Engineering, TU München

- 3-D Biped ***JOHNNIE*** Institute of Applied Mechanics, TU München

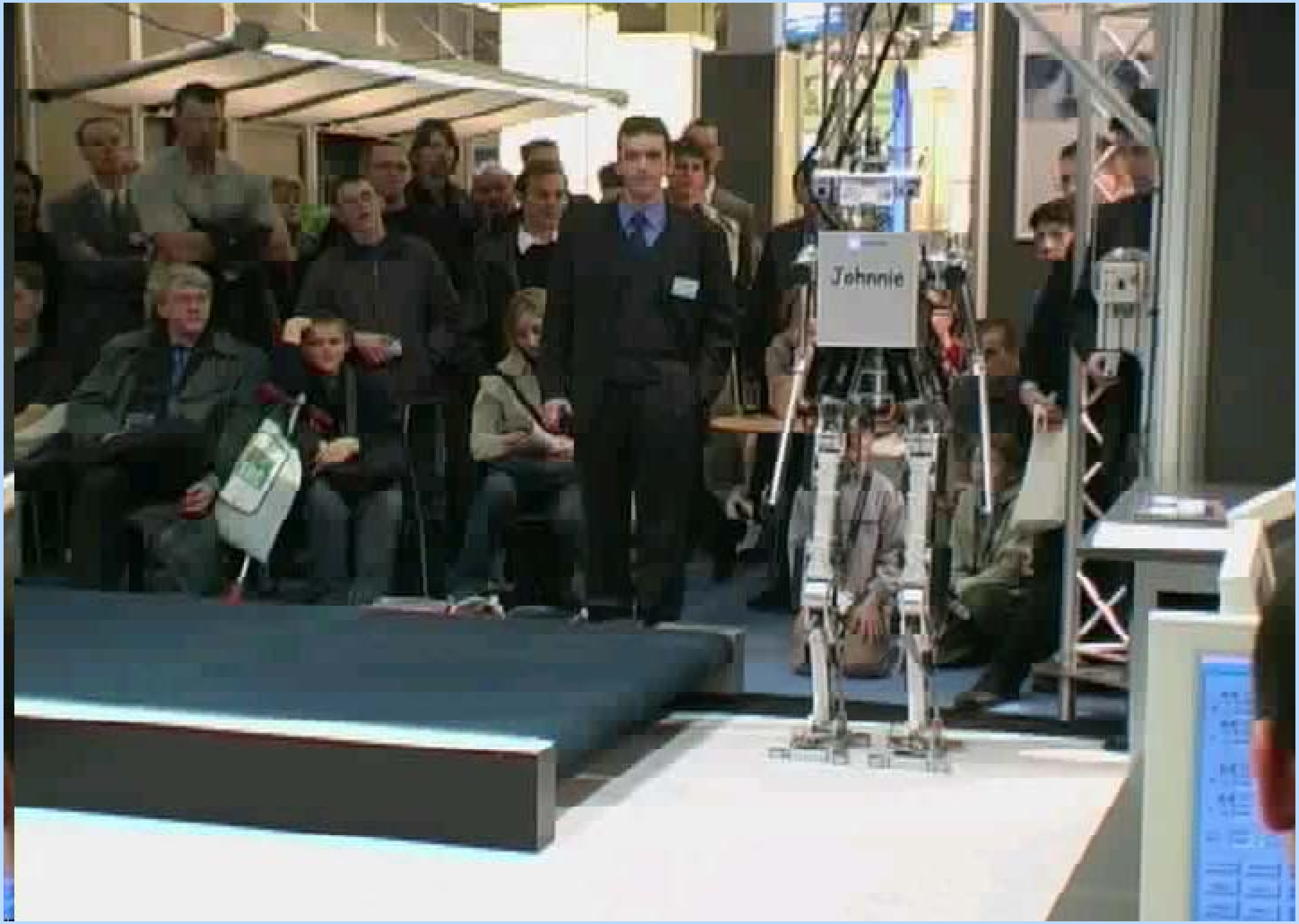
❖ ***M. Gienger, K. Löffler, F. Pfeiffer***
Towards the Design of a Biped Jogging Robot - JOHNNIE
Proc. IEEE Int. Conf. on Robotics and Automation, ICRA 2001, pp. 4140 - 4145.



3-D Walking Scenario

Locomotion Task: "*Walk along U-Shaped Path …*"

http://www.lsr.ei.tum.de/movies/lJohnnie.avi



Conclusions

- "Intelligent" biped walking by incorporation of artificial cognitive control functionalities, e.g. walking and gaze behaviours, . . .
- Flexibility of locomotion by WP Database approach
- In general, classical control methodologies highly supportive for this (new) way of thinking
- Inspiration by analysis of biological prototypes
- Results indicate importance of research in the area of cognitive control methods with application to cognitive vehicles, robots, machines . . . .

Former PhD Students

R	Cupec	Univ. of Osijek, Croatia
J	Denk	Siemens Co.
O	Lorch	BMW Co.
JF	Seara	Boston Consulting Group

THANK YOU
FOR YOUR ATTENTION