Perception-Based Humanoid Robot Walking

- From Automation to Autonomization

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Japan 2004

Motivation

Basis of Locomotion Autonomy
in Humans and Robots ?

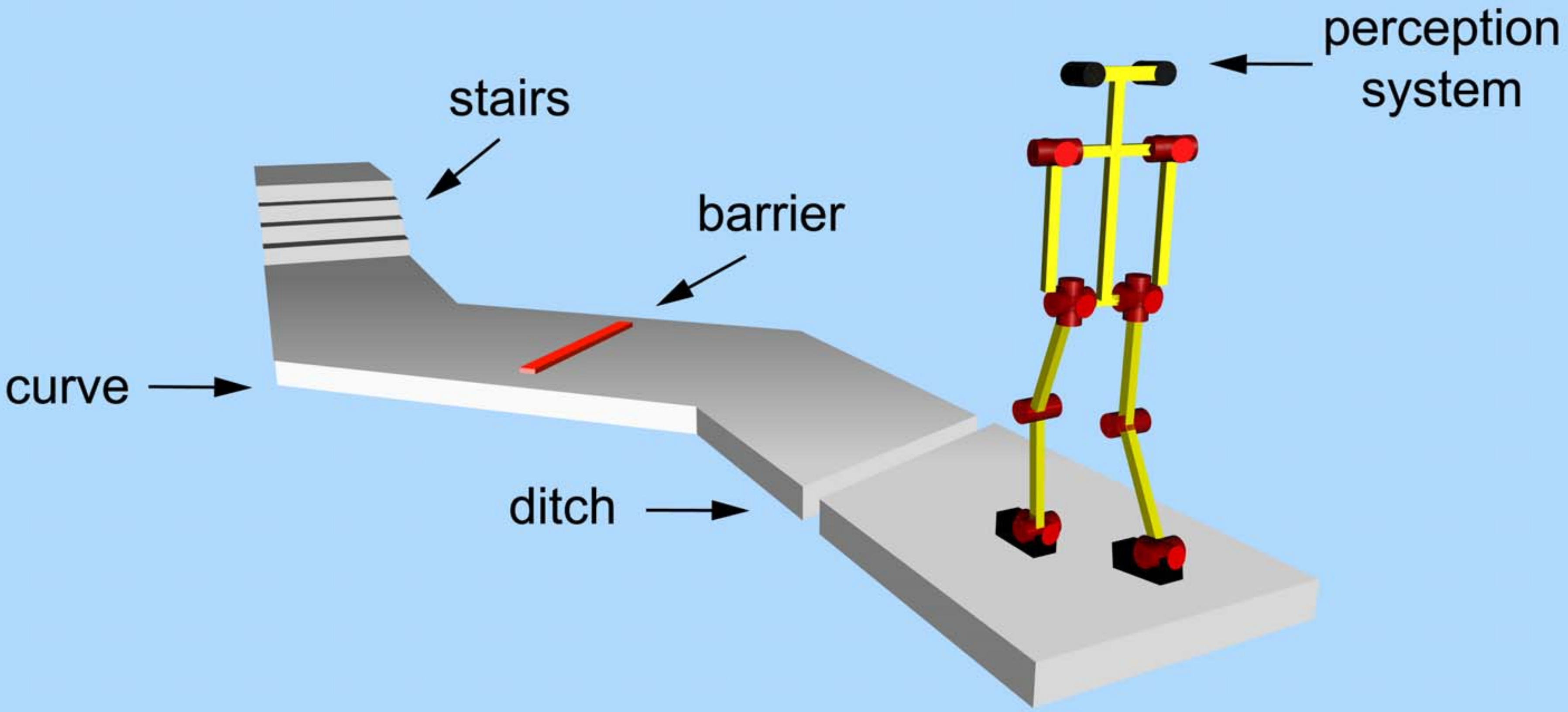
Intelligent Interplay of
Perception and Locomotion:
Cognitive Functionalities

DFG **Project:** ***Autonomous Walking****, 1997 – 2003*

ViGWaM Team:

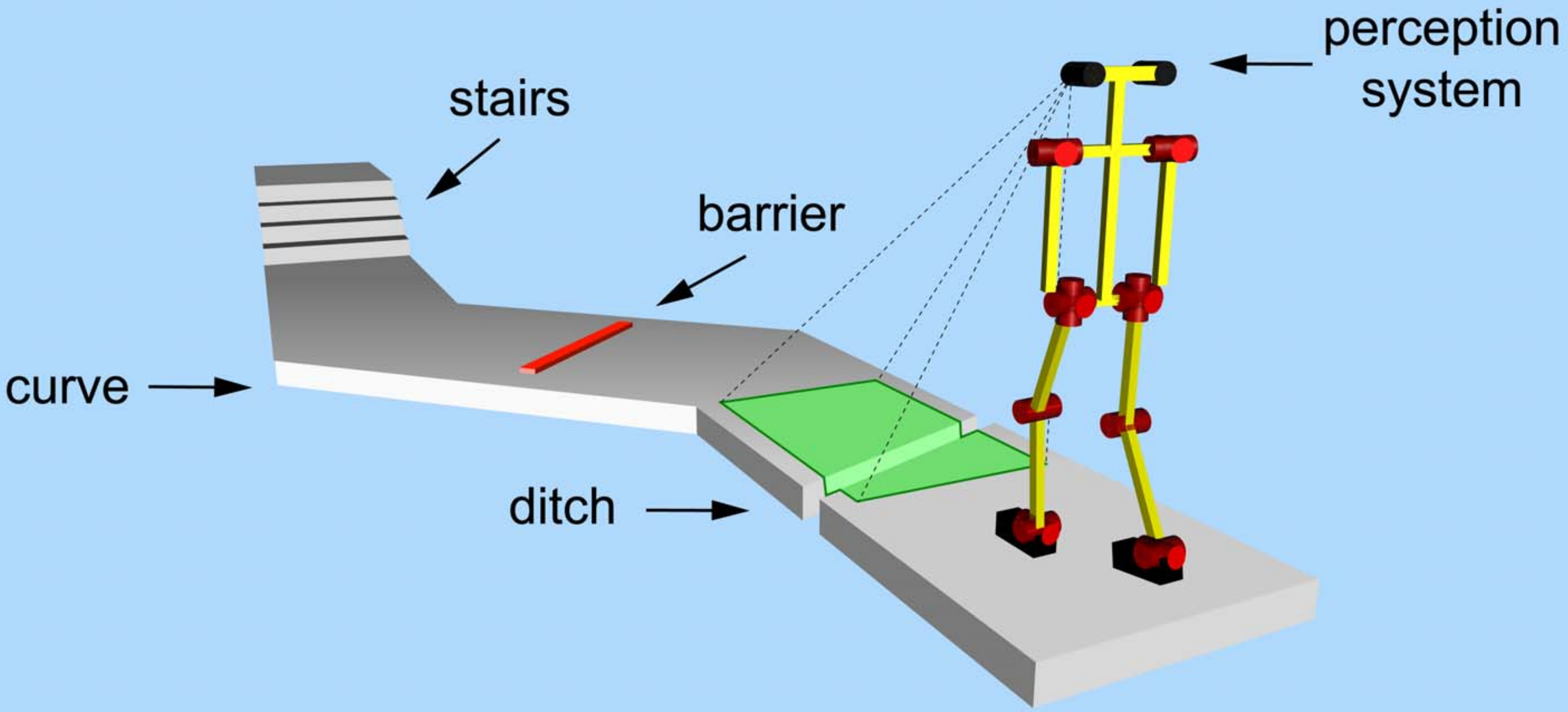
R. Cupec, J. Denk, O. Lorch, J. F. Seara

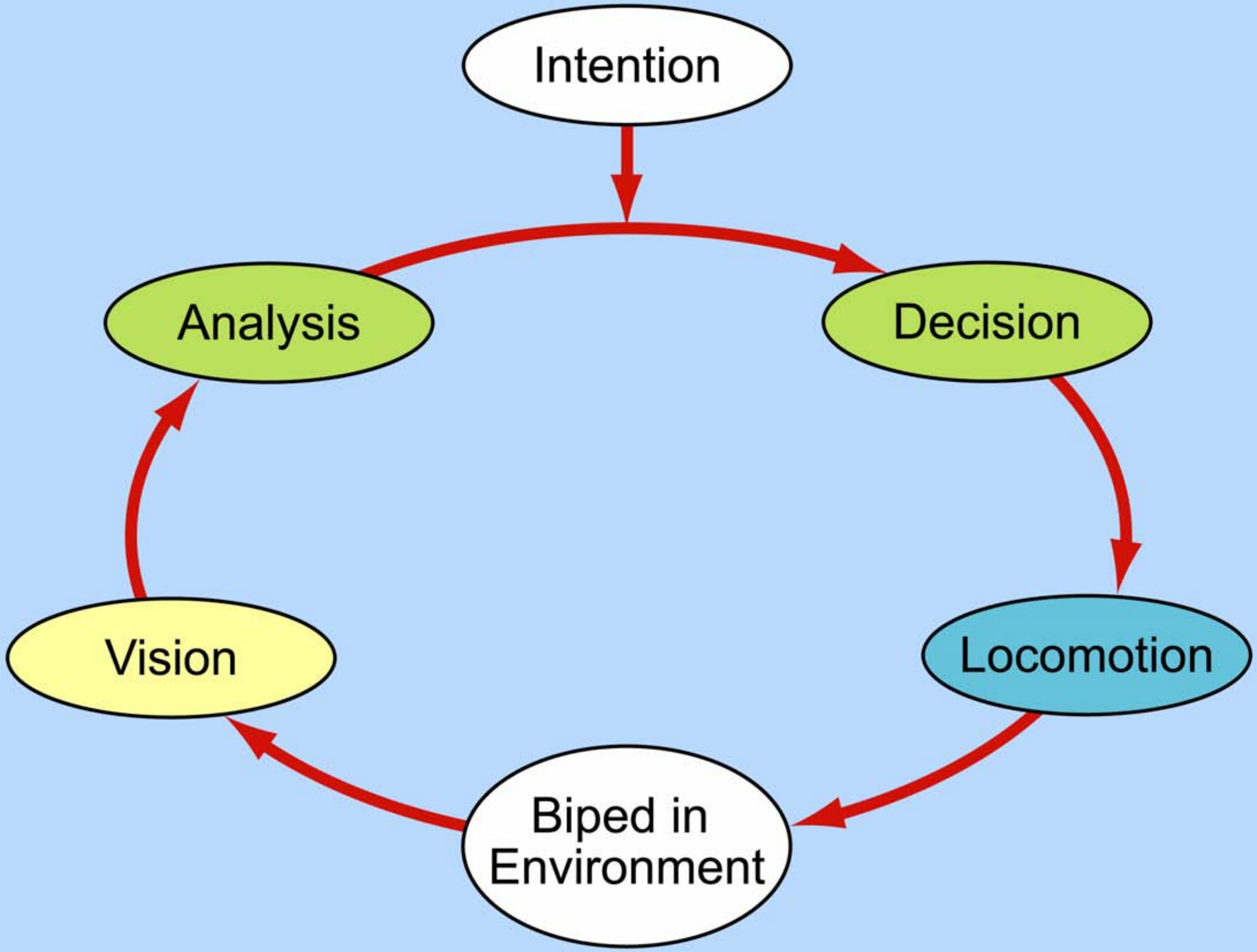
Vision Guided Walking Machine



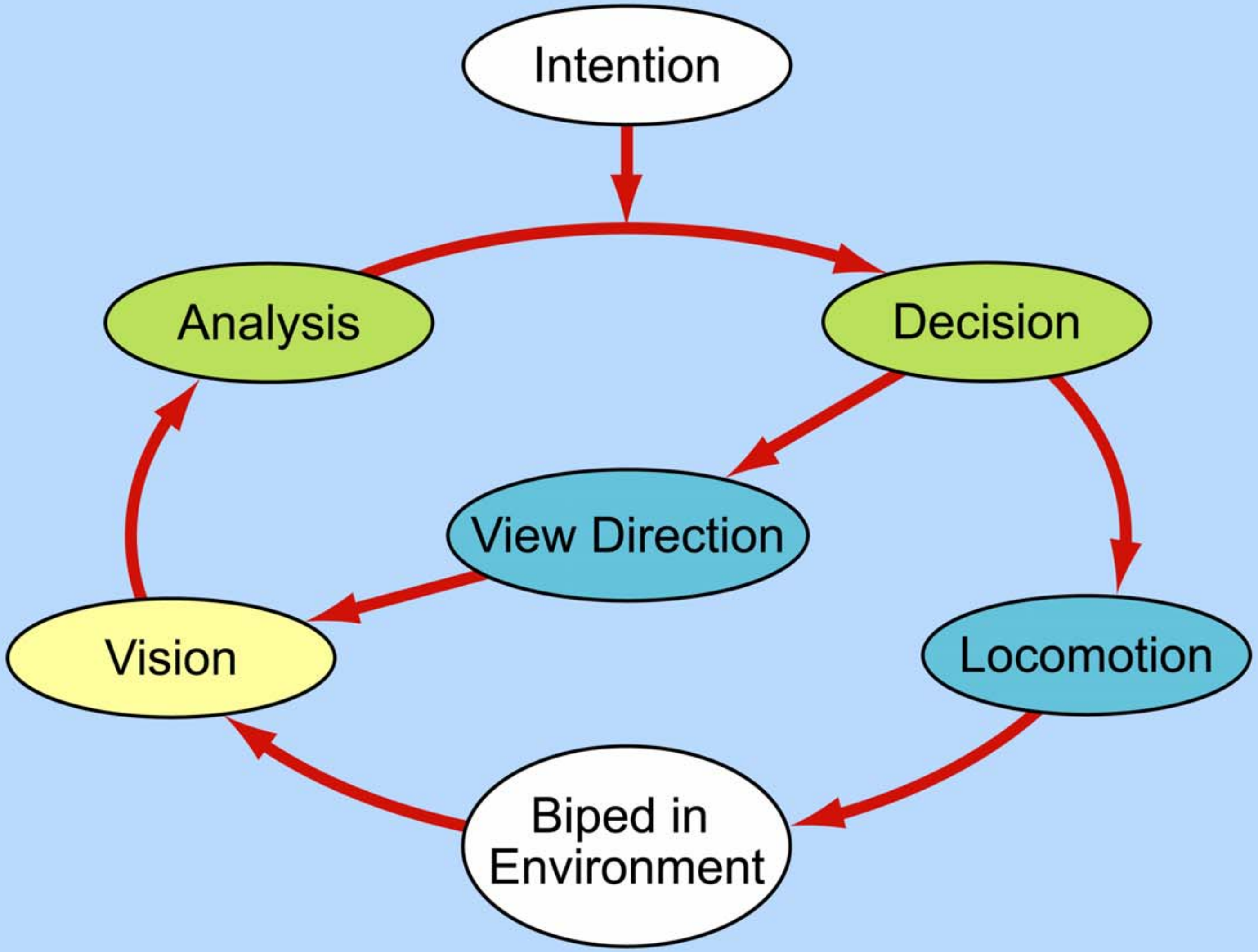
Humanoid Robot in Pedestrian Walk Scenario

"The view anticipates the step"





Information Flow in Vision-Guided Locomotion

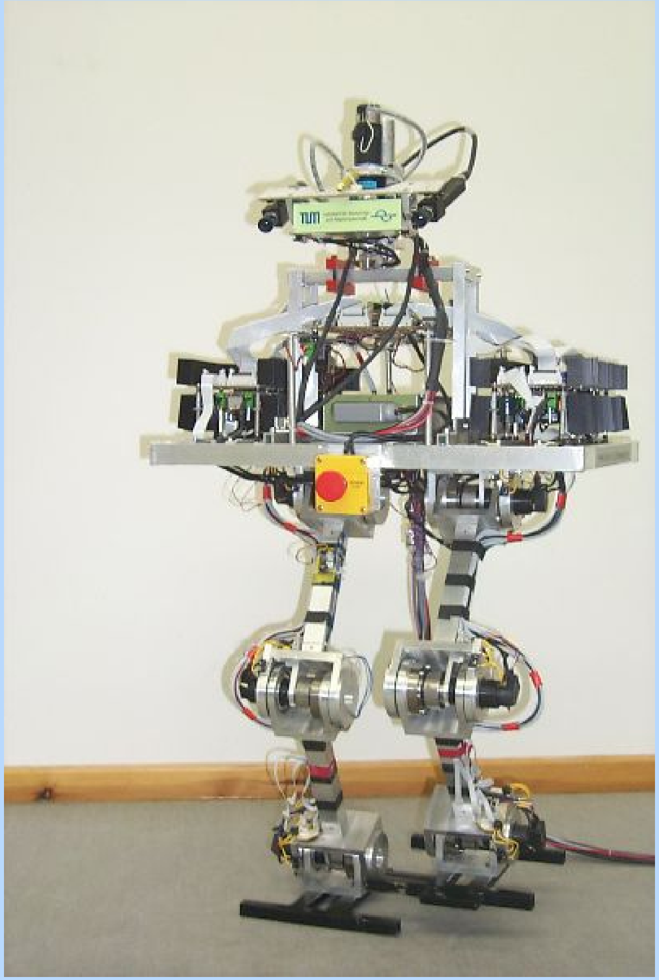


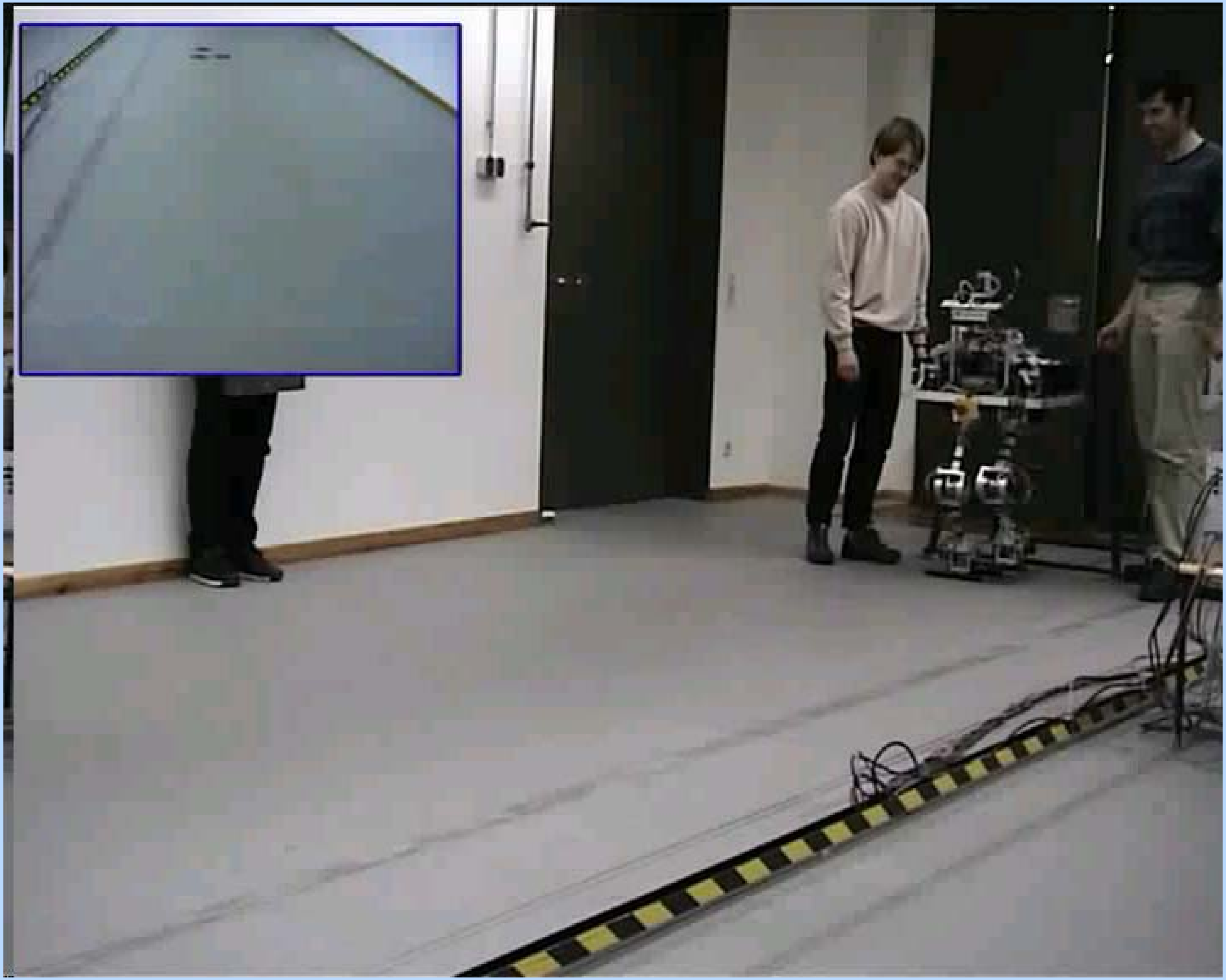
Information Flow in Vision-Guided Locomotion

Cooperation Project

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

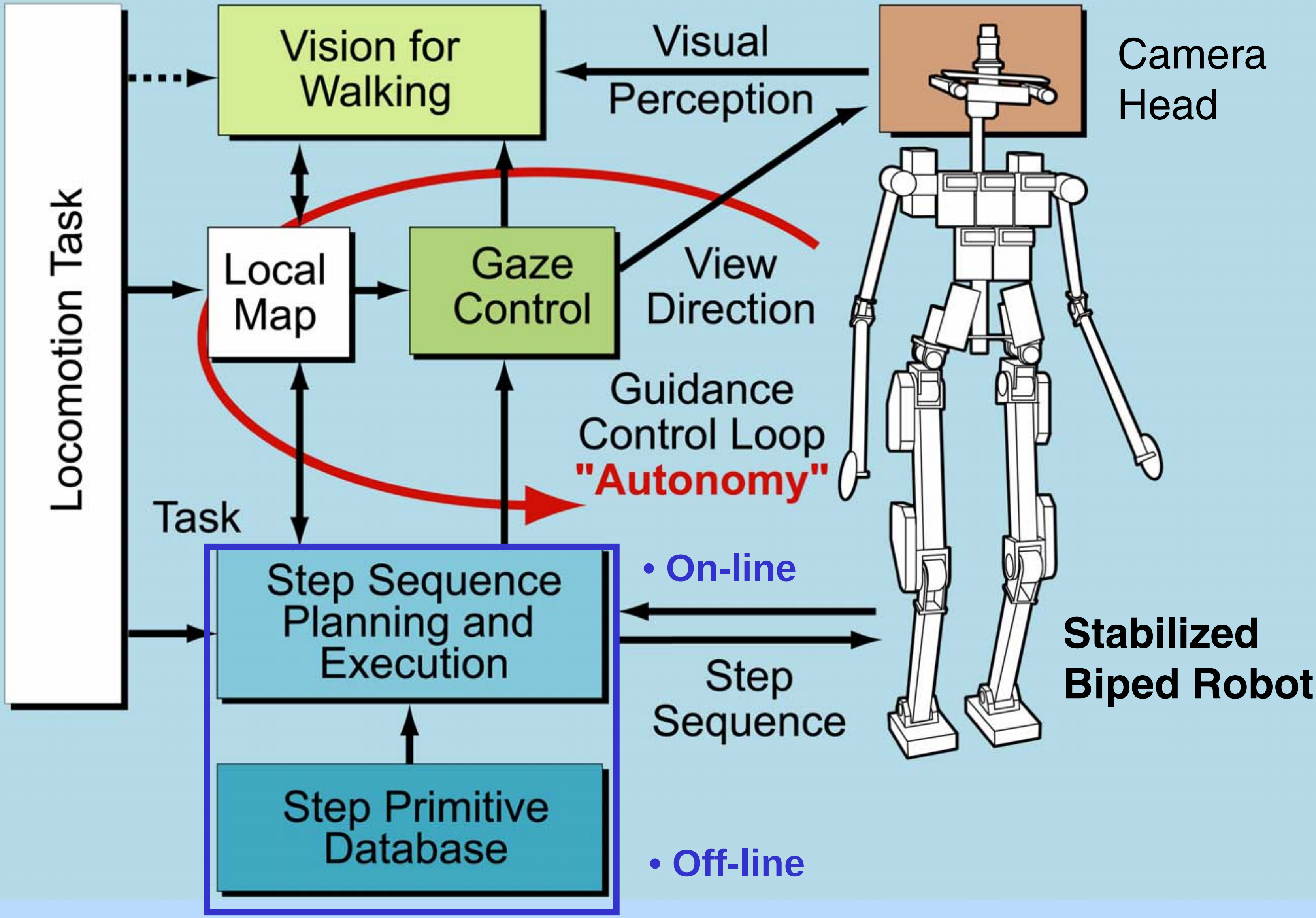
- Stabilized Walking Machine, Institute of Automatic Control, Uni Hannover





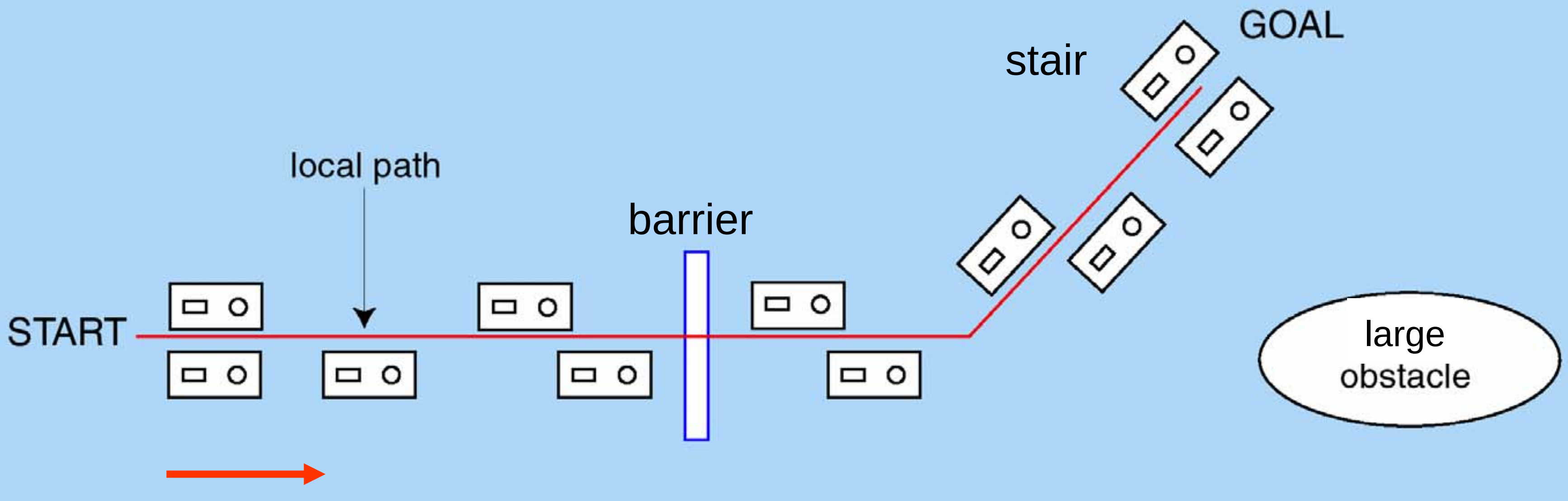
Reactive Walking:
Obstacle Avoidance and Step Trace Following

Architecture of Visual Guidance System


Locomotion Task
Vision for Walking
Visual Perception
Camera Head
Local Map
Gaze Control
View Direction
Guidance Control Loop
"Autonomy"
Task
Step Sequence Planning and Execution
• On-line
Step Sequence
Stabilized Biped Robot
Step Primitive Database
• Off-line

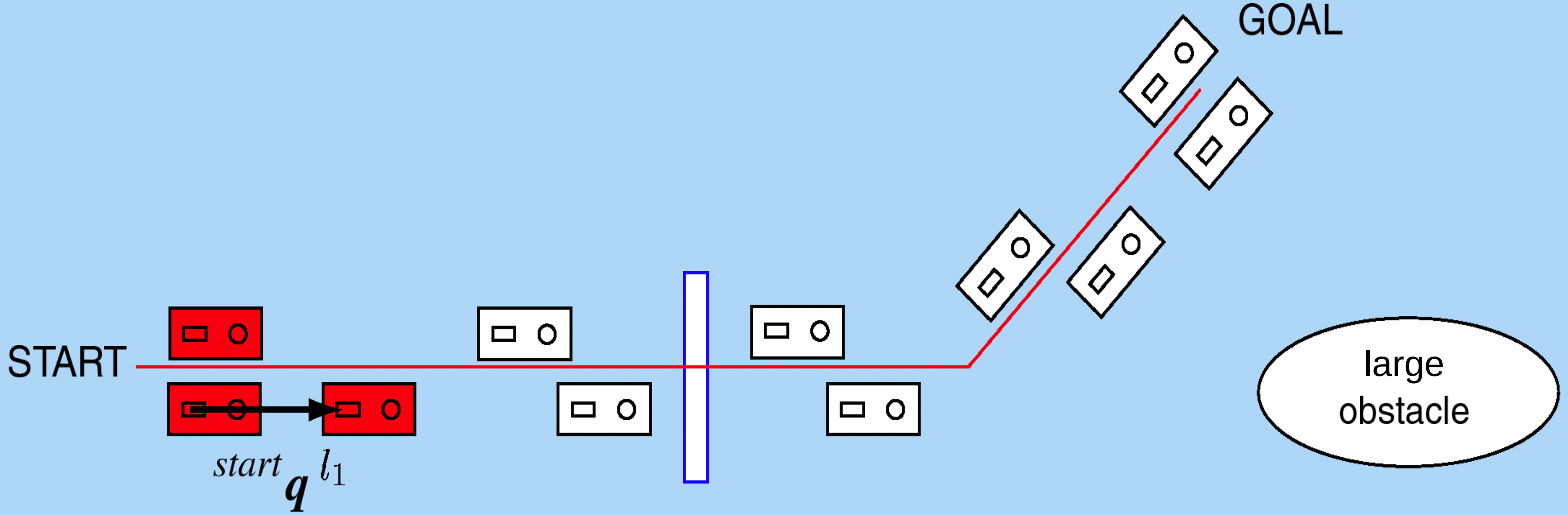
Step Primitives
for Continuous Biped Walking

= Step Sequence Planning – offline



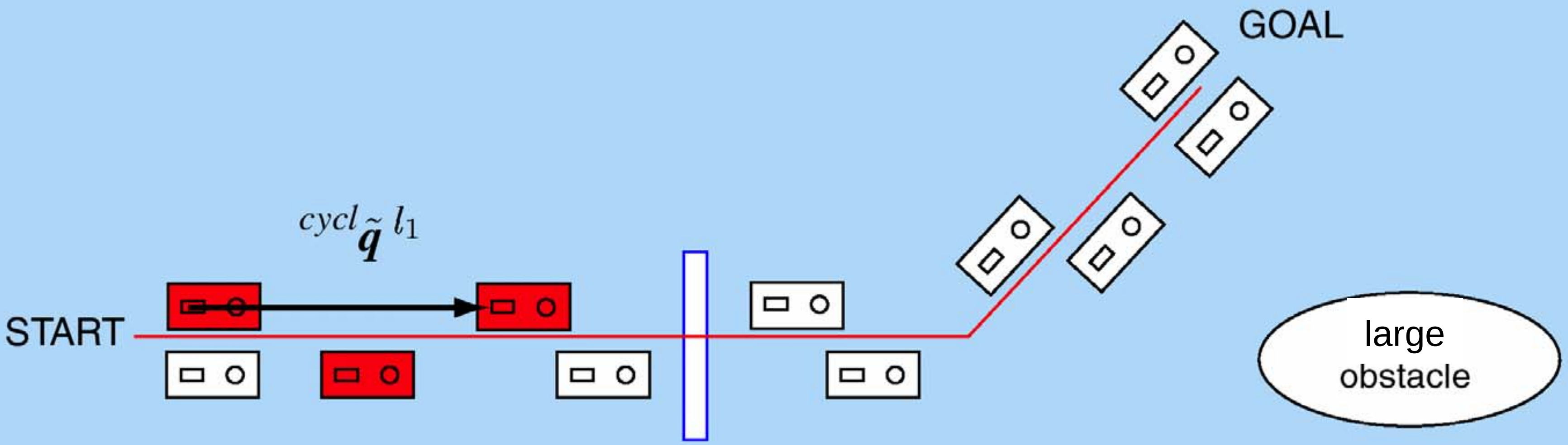
Locomotion Capabilities required by Biped ?

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



Step Primitives
for statically or dynamically stable walking:

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



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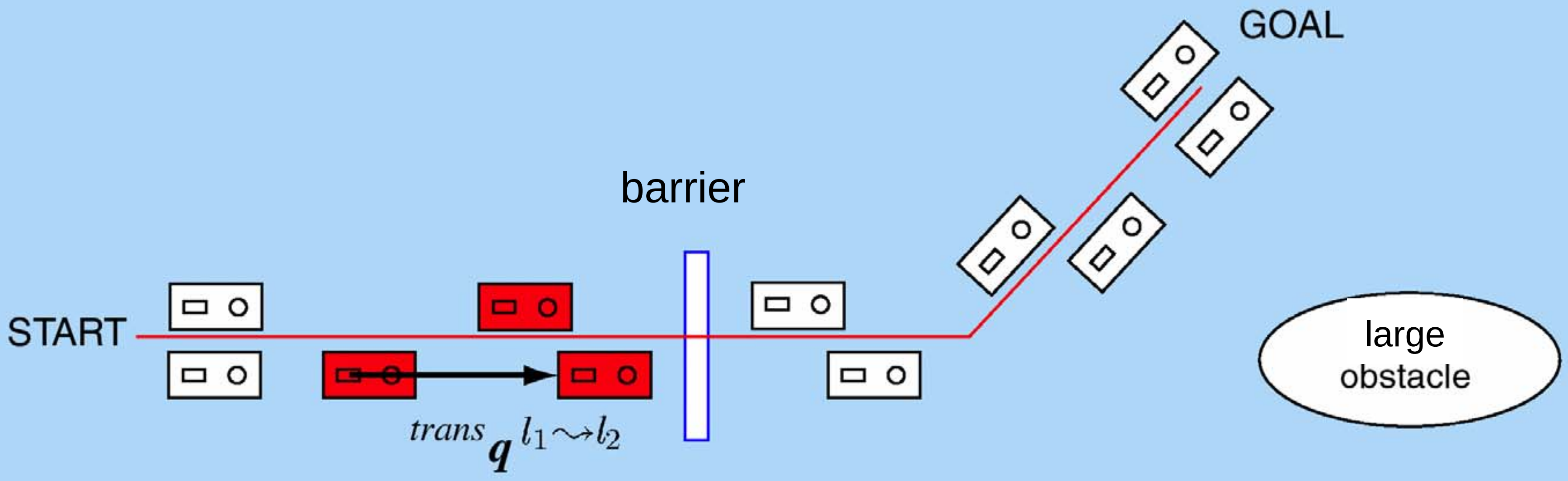

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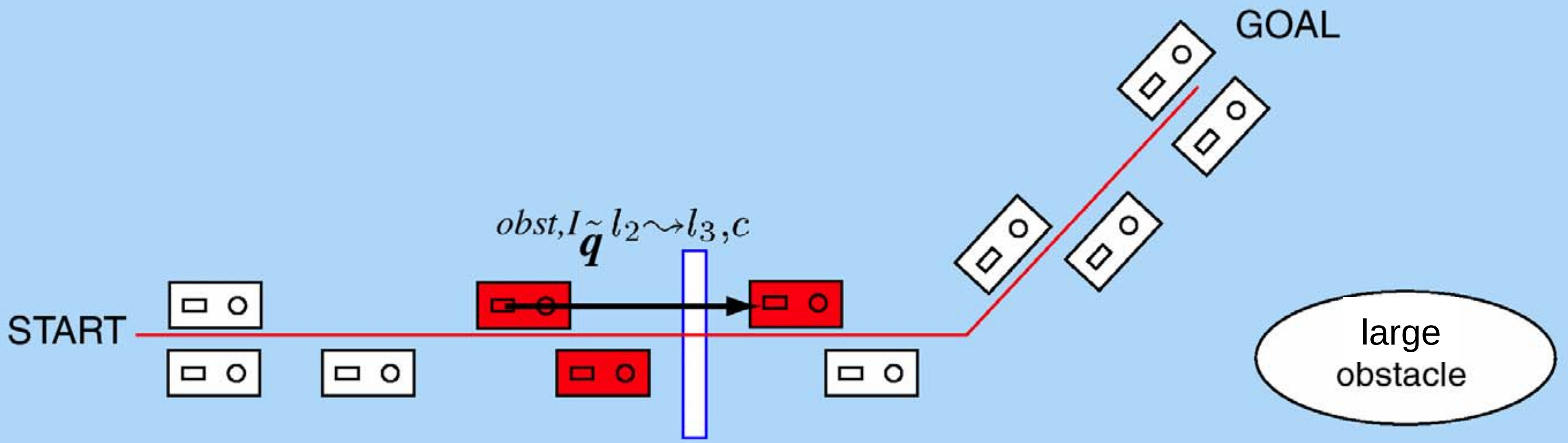

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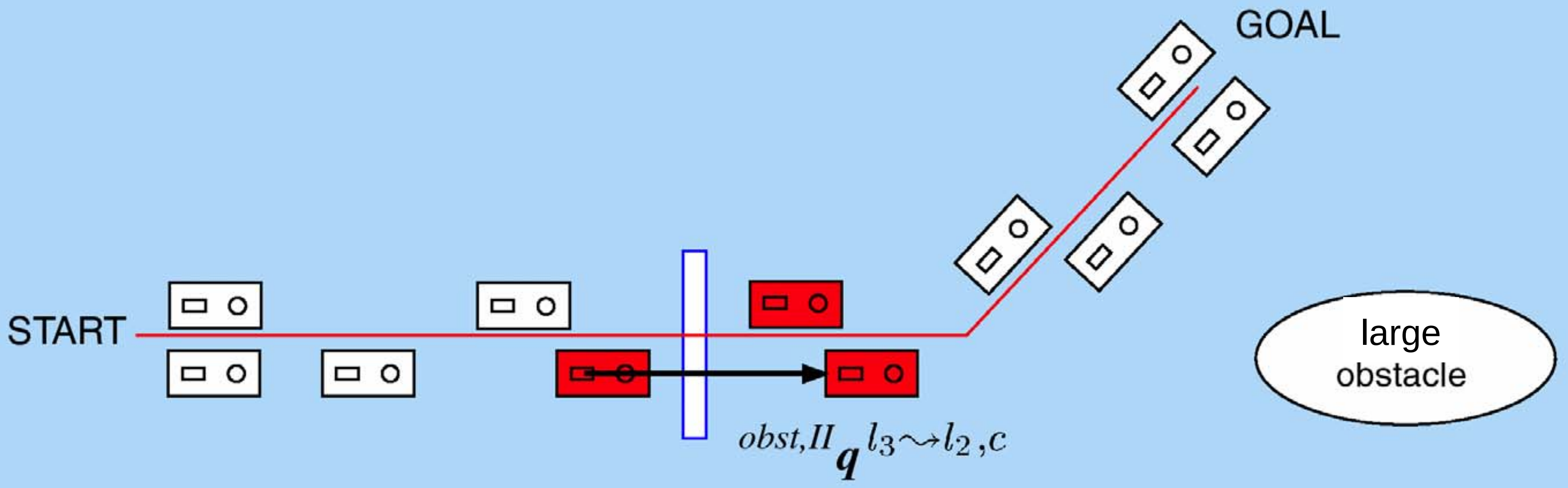

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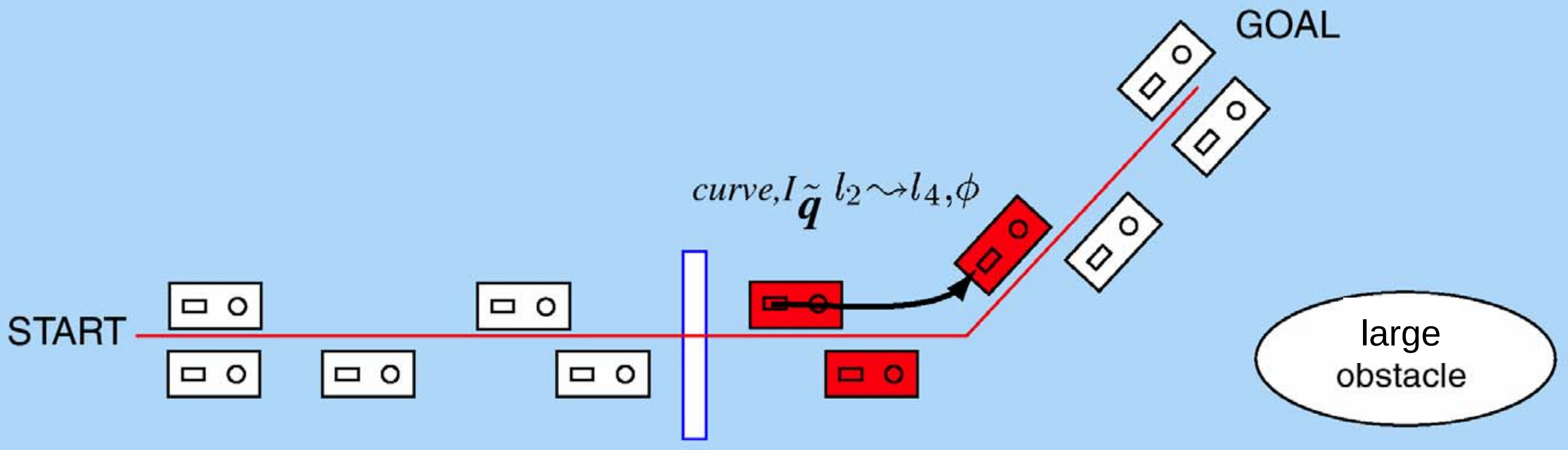

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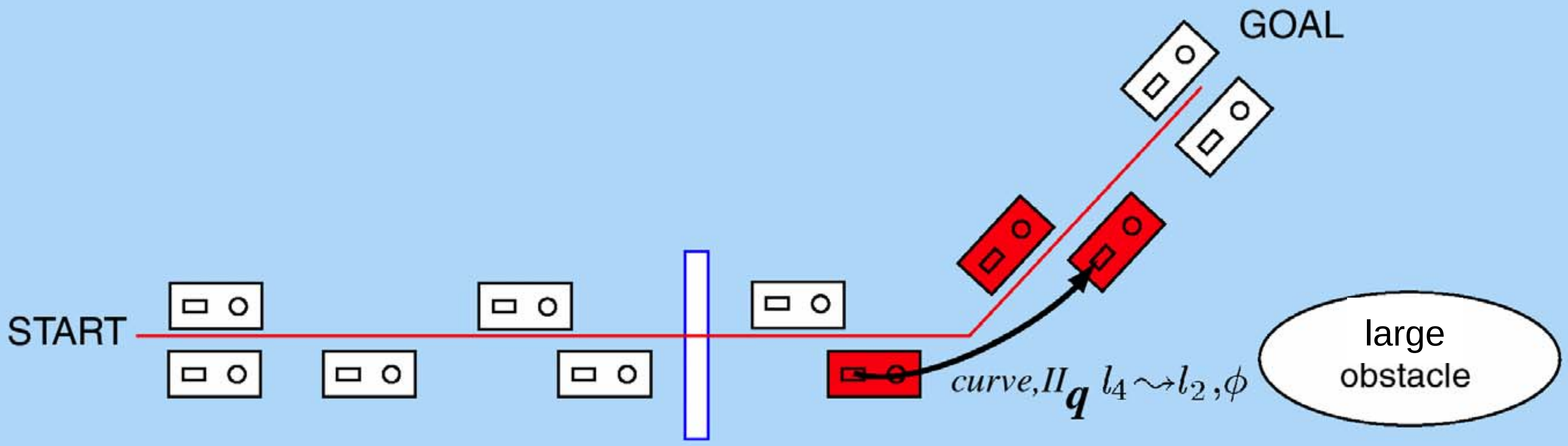

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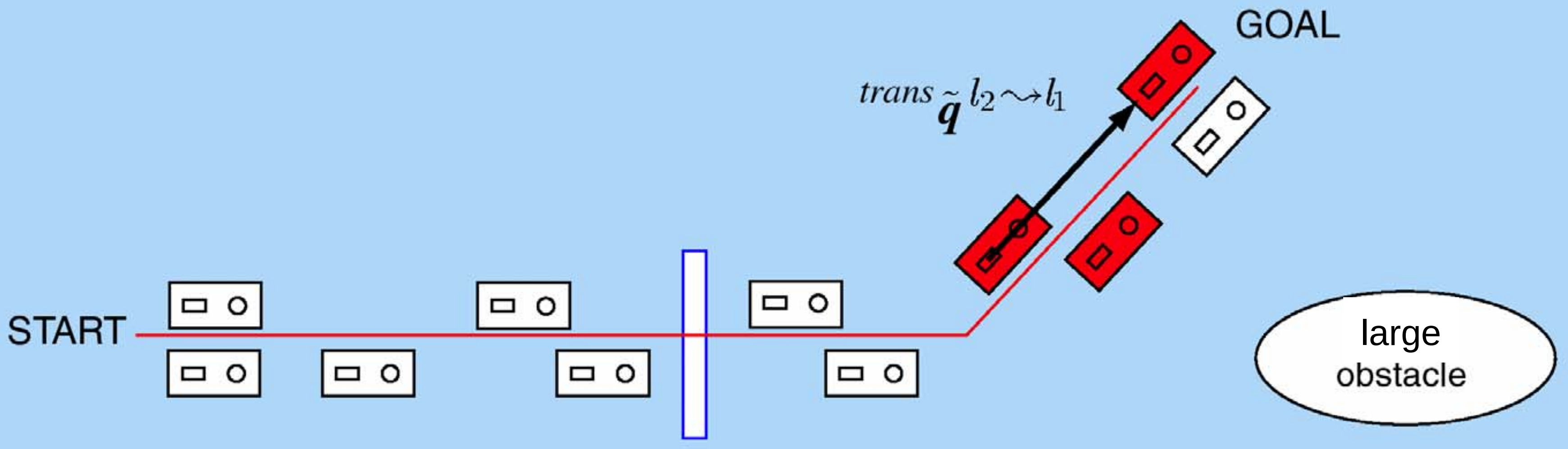

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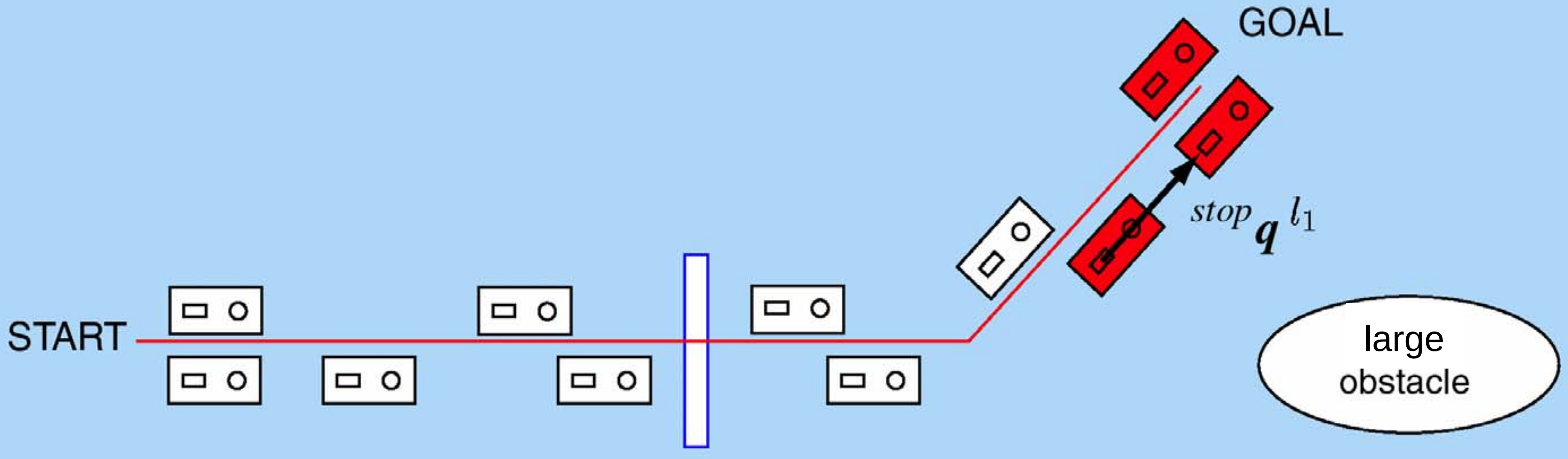

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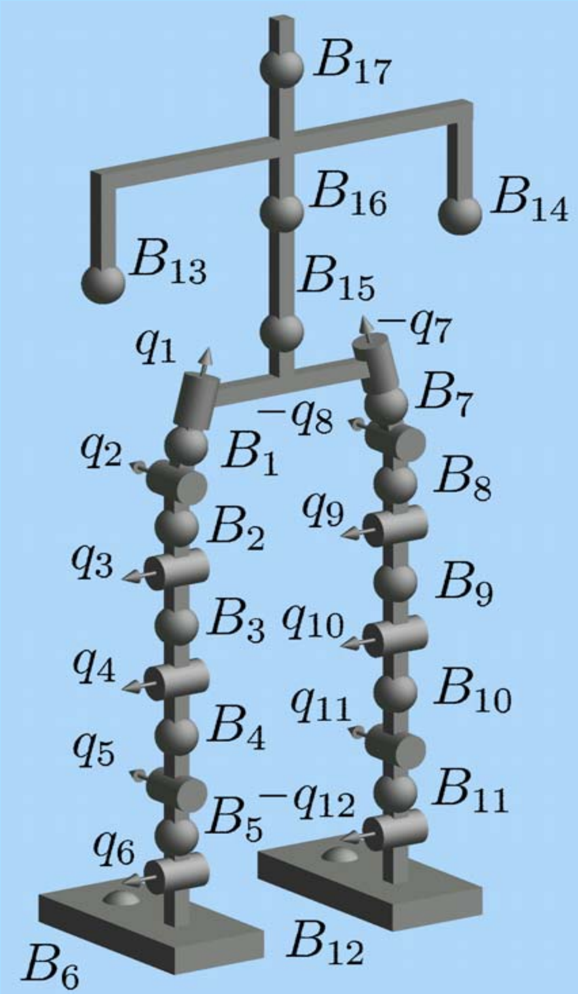
- stair primitives

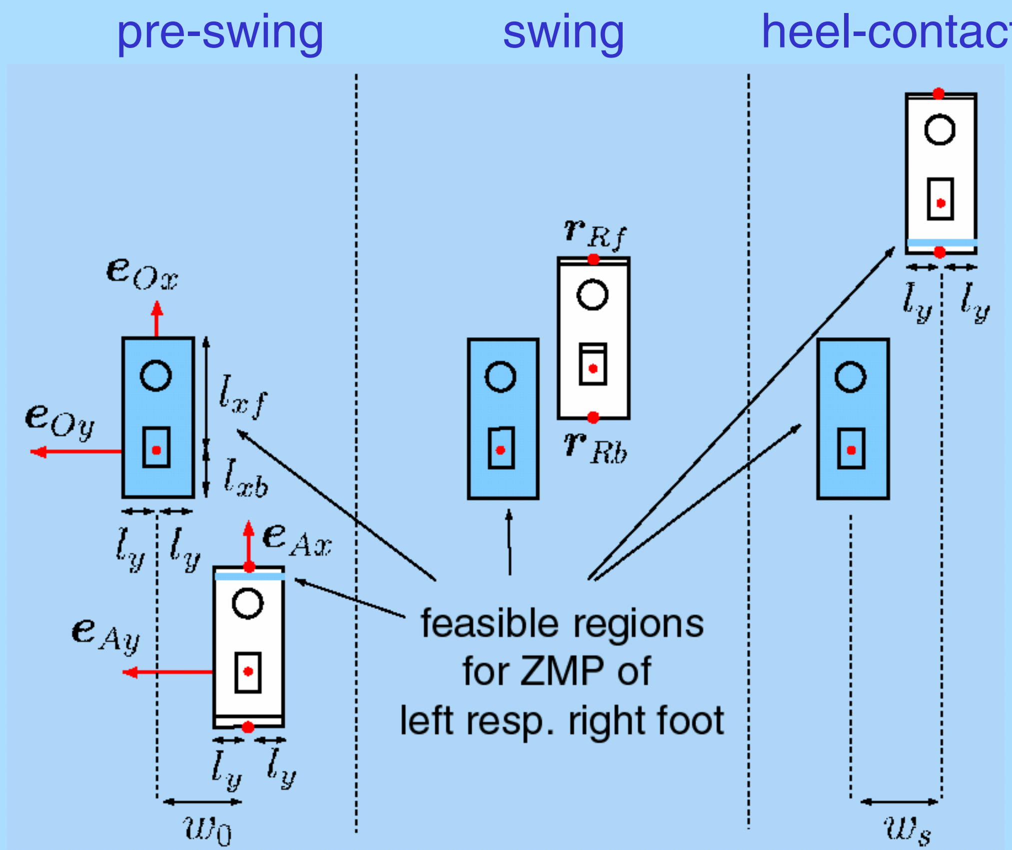
Computation of Joint Torques for Step Primitive Data Base

= Step Sequence Planning – offline

Kinetic Robot Model

3 Locomotion Phases:





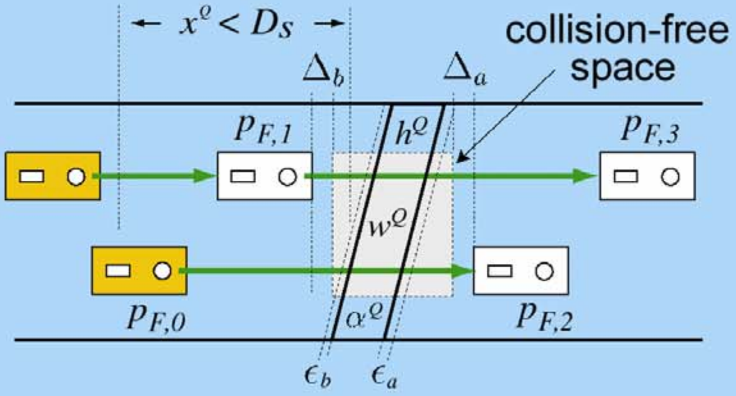
$$\min_{\boldsymbol{\tau}(t)} \left[\int_0^{t_1} \sum_{i=1}^{N_j} |\dot{q}_i(t)\tau_i(t)|\,dt + \int_{t_1}^{t_2} \left(\sum_{i=1}^{N_j} |\dot{q}_i(t)\tau_i(t)| + \sum_{j=1}^{4} e^{\alpha(\epsilon - r_{R_j,z})} \right) dt + \int_{t_2}^{t_s} \sum_{i=1}^{N_j} |\dot{q}_i(t)\tau_i(t)|\,dt \right]$$

3-Phase Optimization with Objectives: Stability and Minimal Energy

Step Sequence-Generation by Concatenation of Step Primitives from Data Base

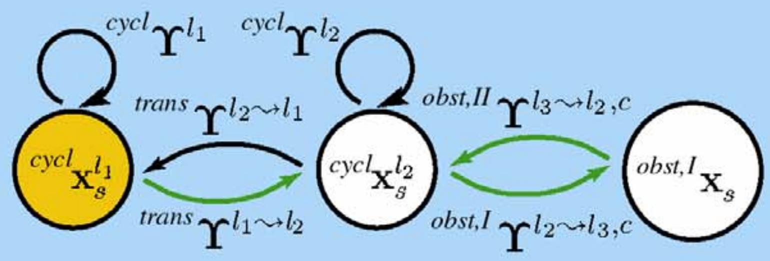
= Step Sequence Planning - online

(i) Obstacle Situation: e.g. barrier



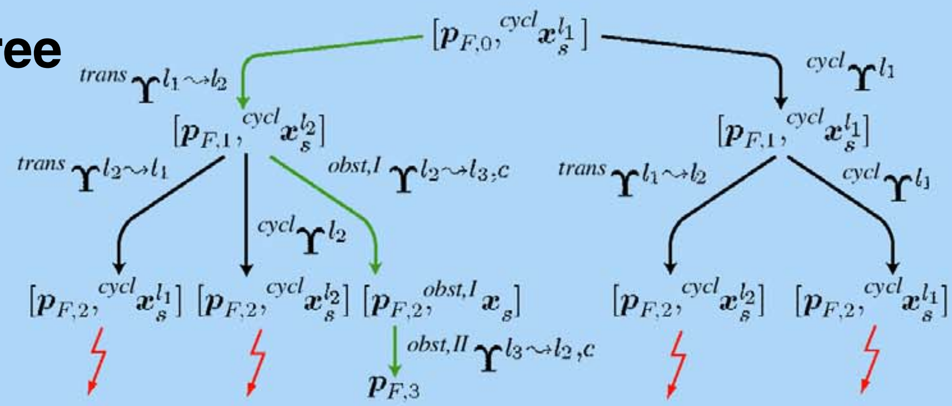
Situation ahead of a barrier

(ii) Representation of Step Primitives by Graph



Knowledge base with walking primitives
(≅ human experience gained by learning)

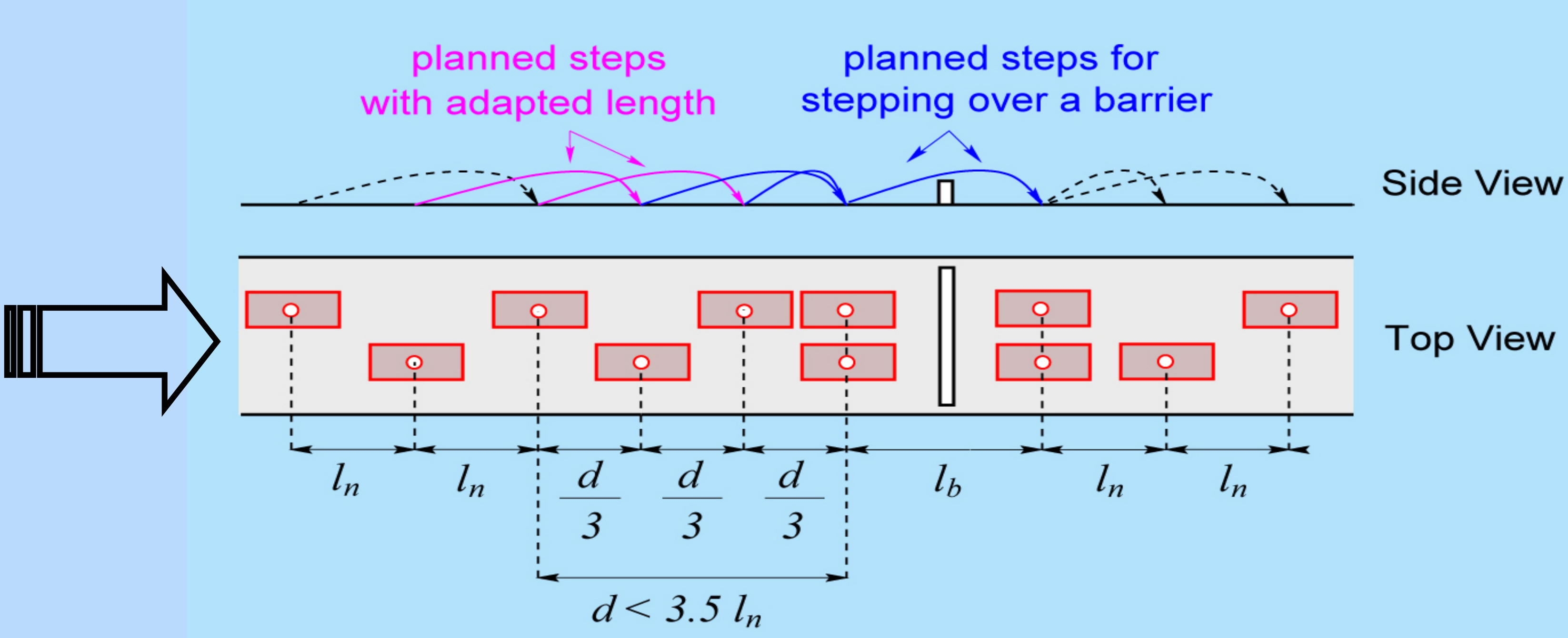
(iii) Search Tree



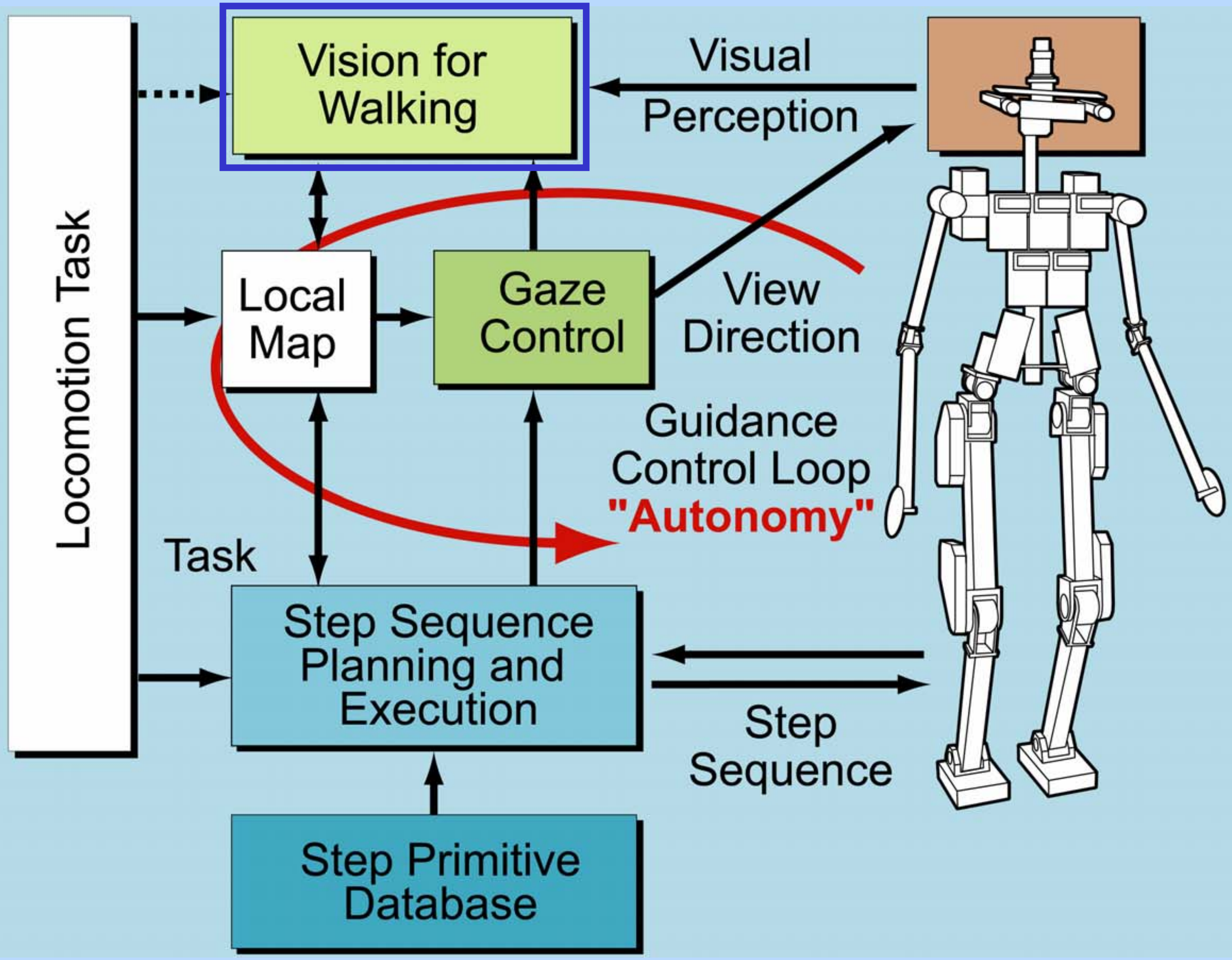
Search tree by evaluation of graph structure and perception
(Multiple solutions allow task dependent choice of appropriate step sequence)

"3-Steps-Ahead-Strategy"

$$l = \begin{cases} d/3 & \text{for} \quad 3.5\, l_n \geq d > 2.5\, l_n \\ d/2 & \text{for} \quad 2.5\, l_n \geq d > 1.5\, l_n \\ d & \text{for} \quad 1.5\, l_n \geq d > 0.5\, l_n \end{cases}$$



Robot Vision
for Autonomous Locomotion
= Vision for Walking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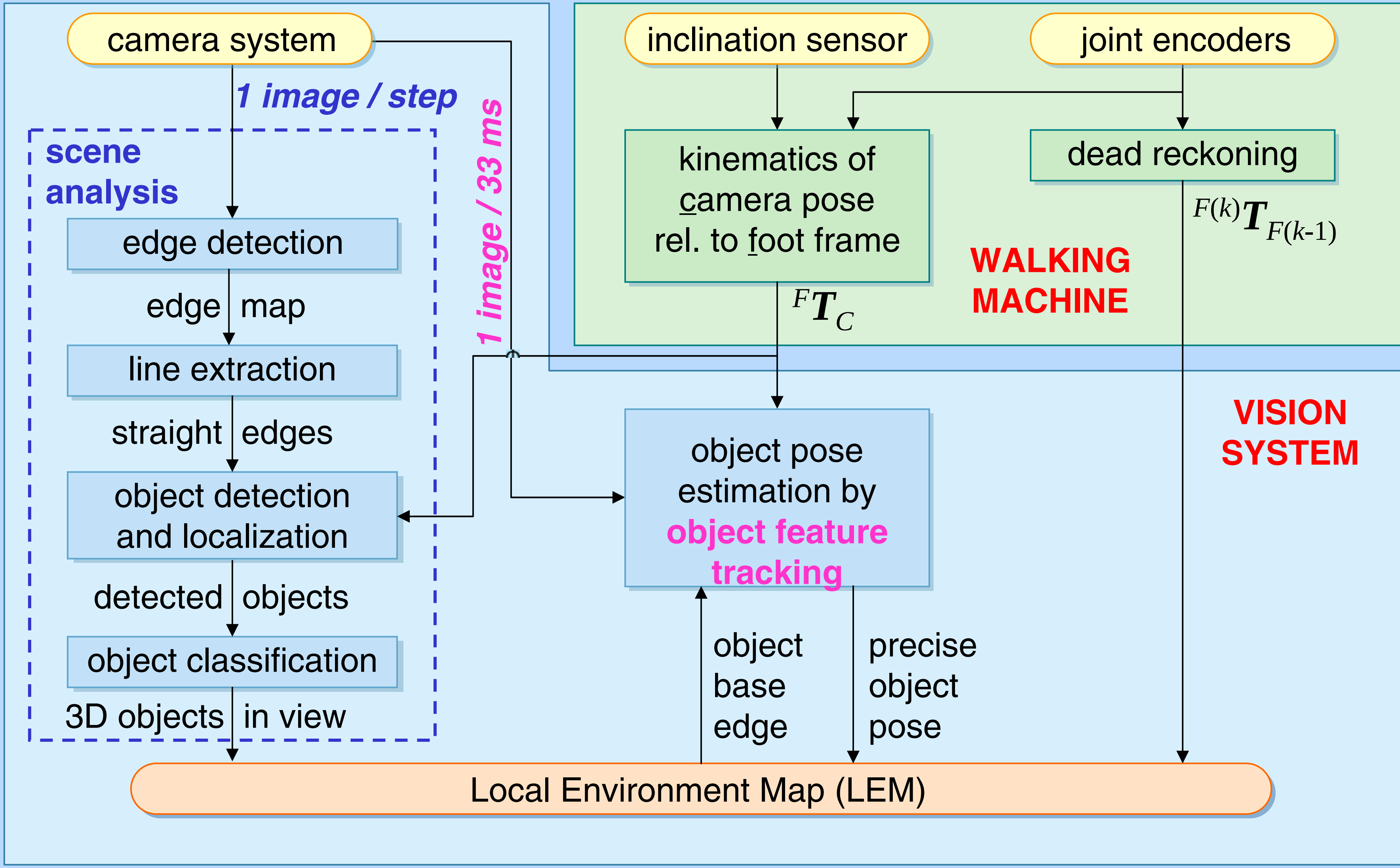
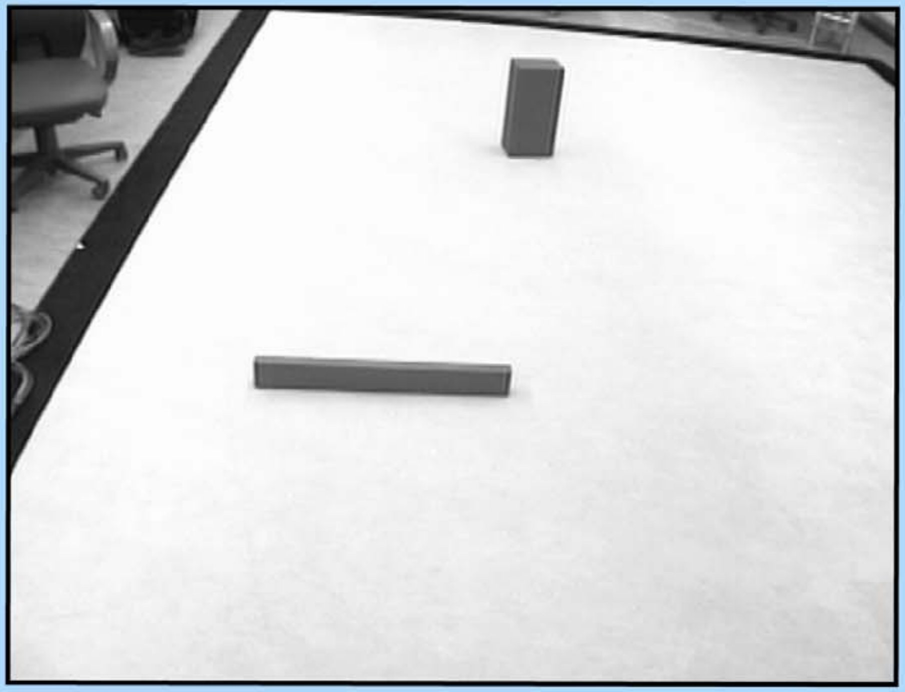
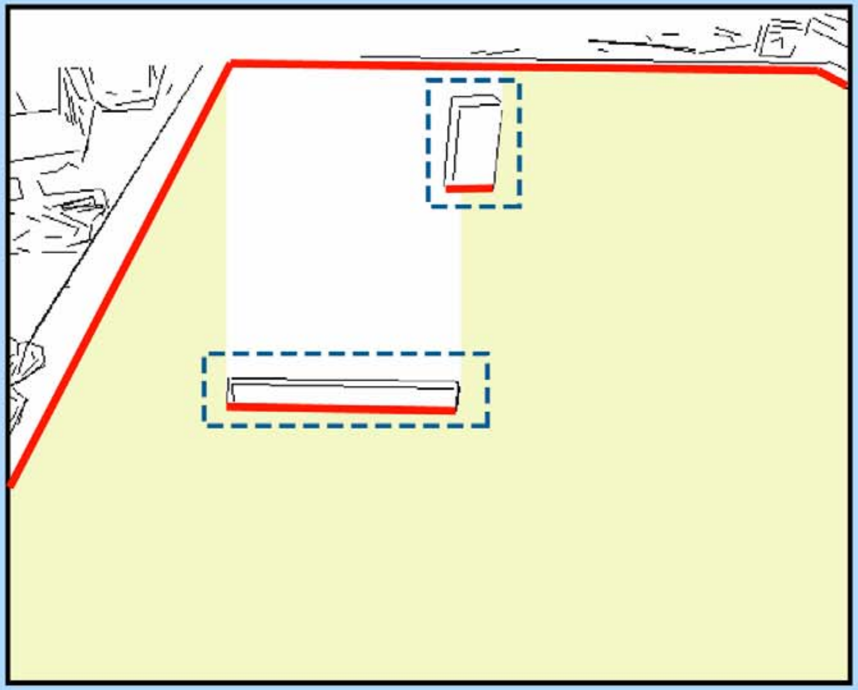


Architecture of Perception Approach



left camera image



detected lines

base edges

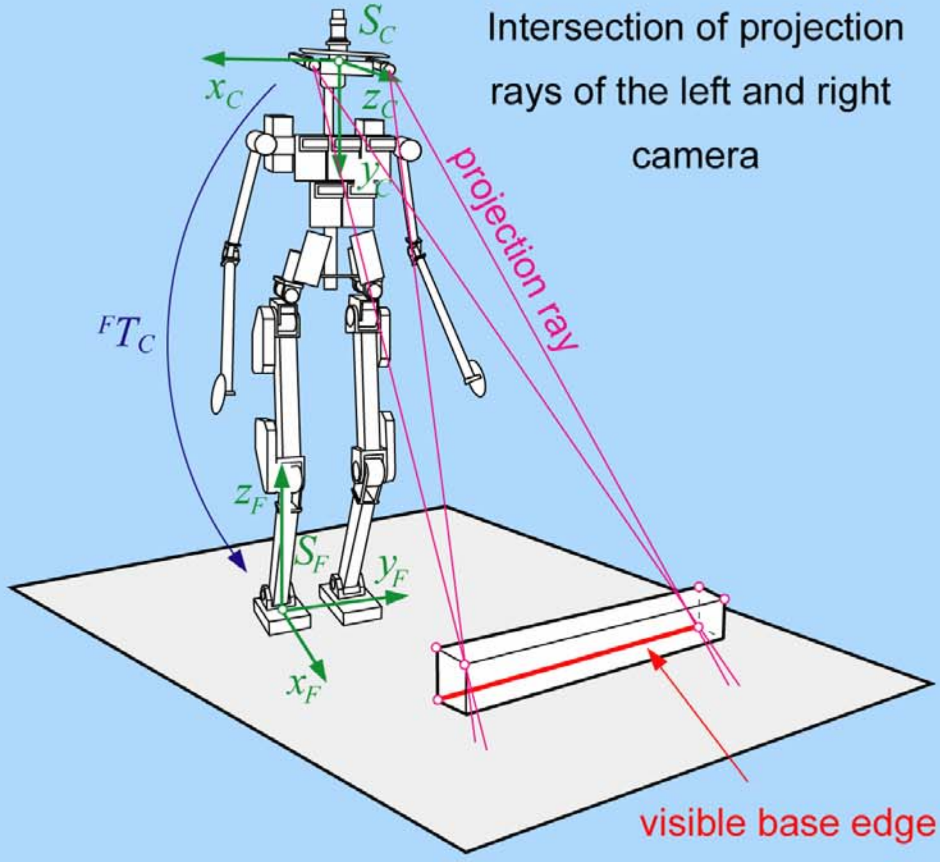
obstacles

obstacle free area ahead of the next obstacles

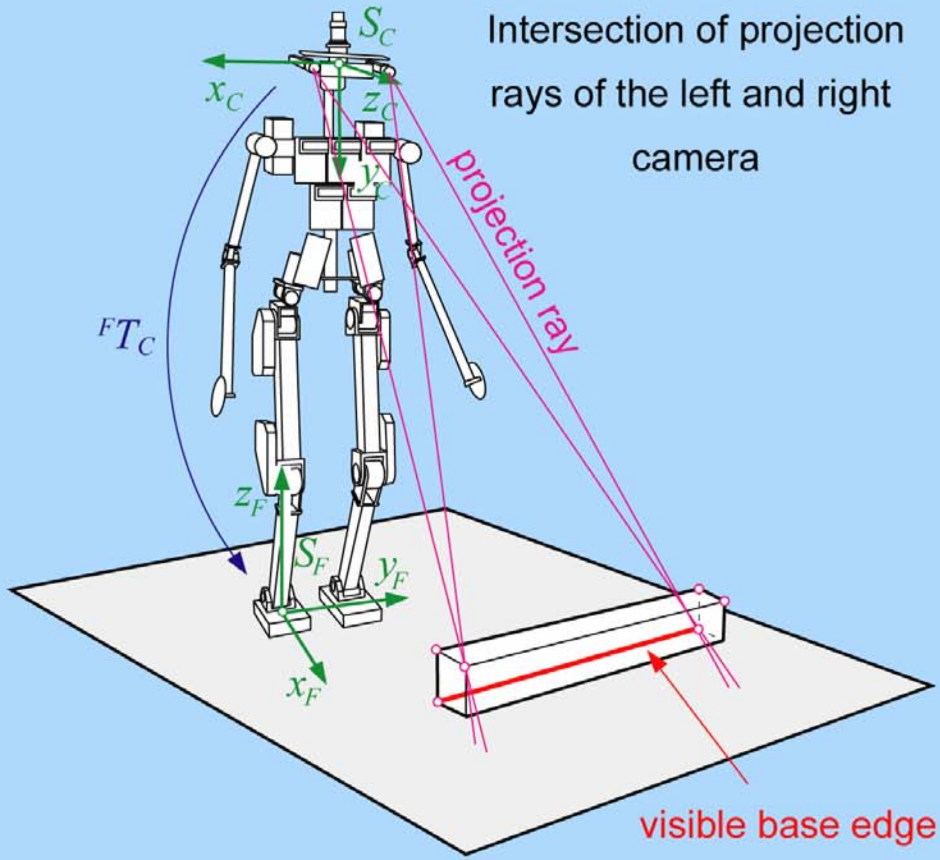
Phase #1:
Line Extraction and Object Detection (= Segmentation)

Stereo Vision + Kinematics (+ Inclination Sensor)

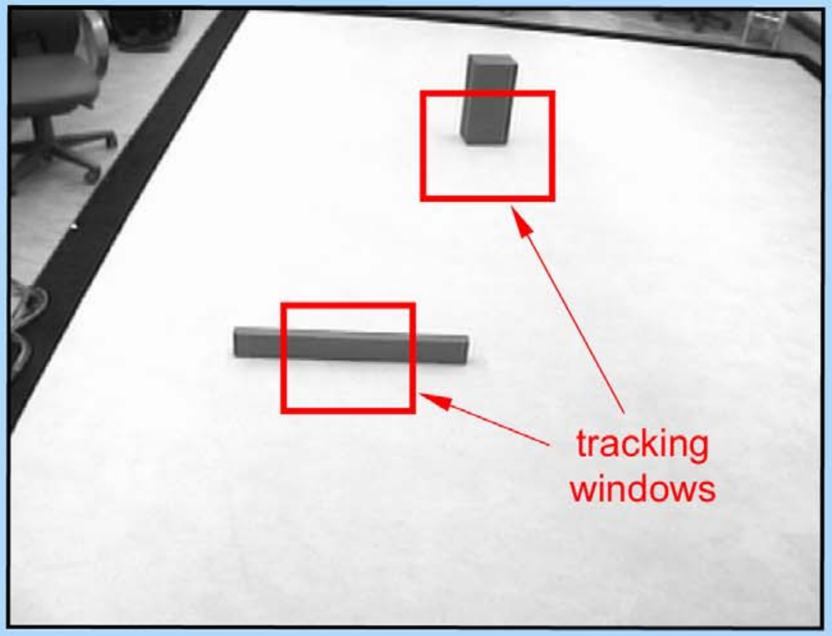
Intersection of projection rays of the left and right camera



Stereo Vision + Kinematics (+ Inclination Sensor)



Precise Localization by Real-Time Feature Tracking



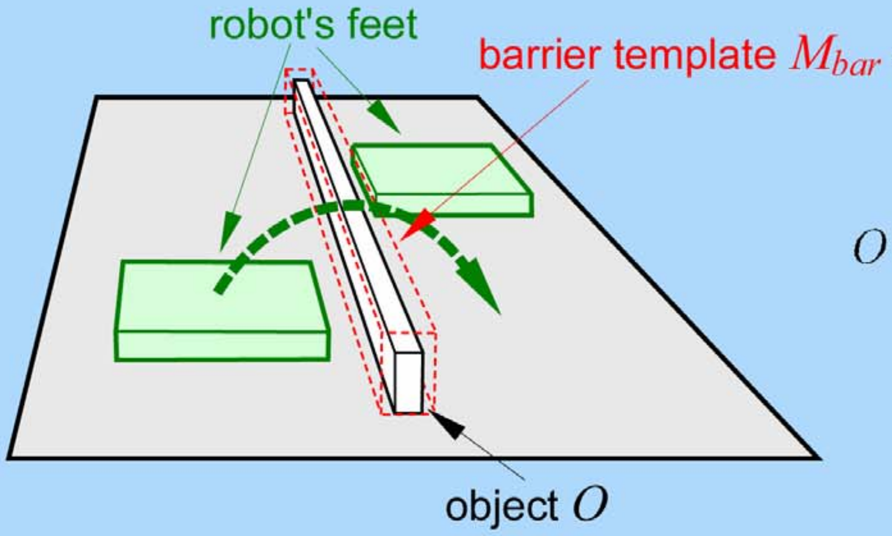
Phase #2b:

Obstacle Localisation and Feature Tracking

Decision-Making:

Locomotion action required
w.r.t. current obstacle situation?

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



defined by mechanical abilities of the walking machine

$O \subset M_{bar}$ → O is a barrier

Phase 3a:

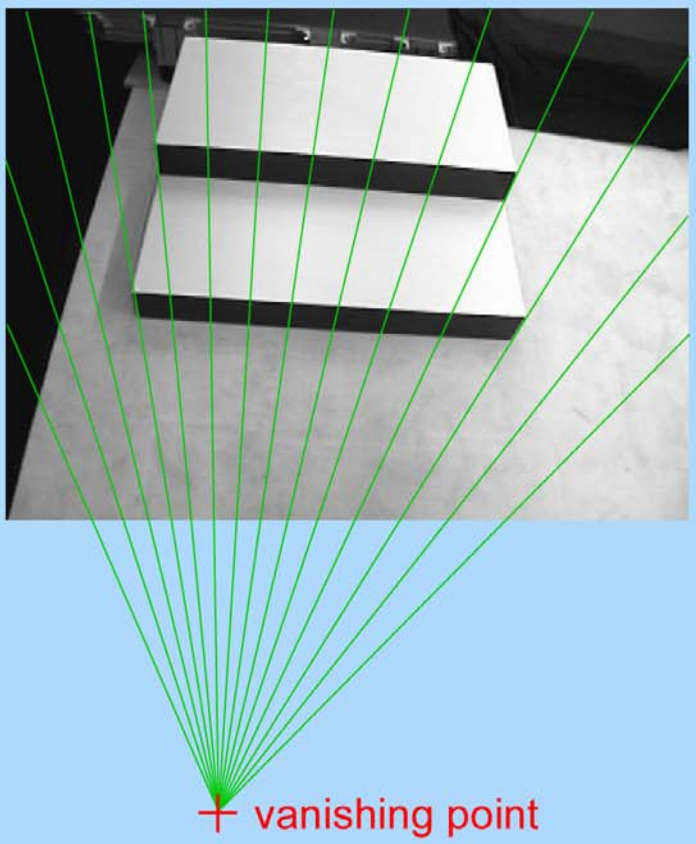
Obstacle Classification, e.g. Barrier, Stairs, Wall

Step 1

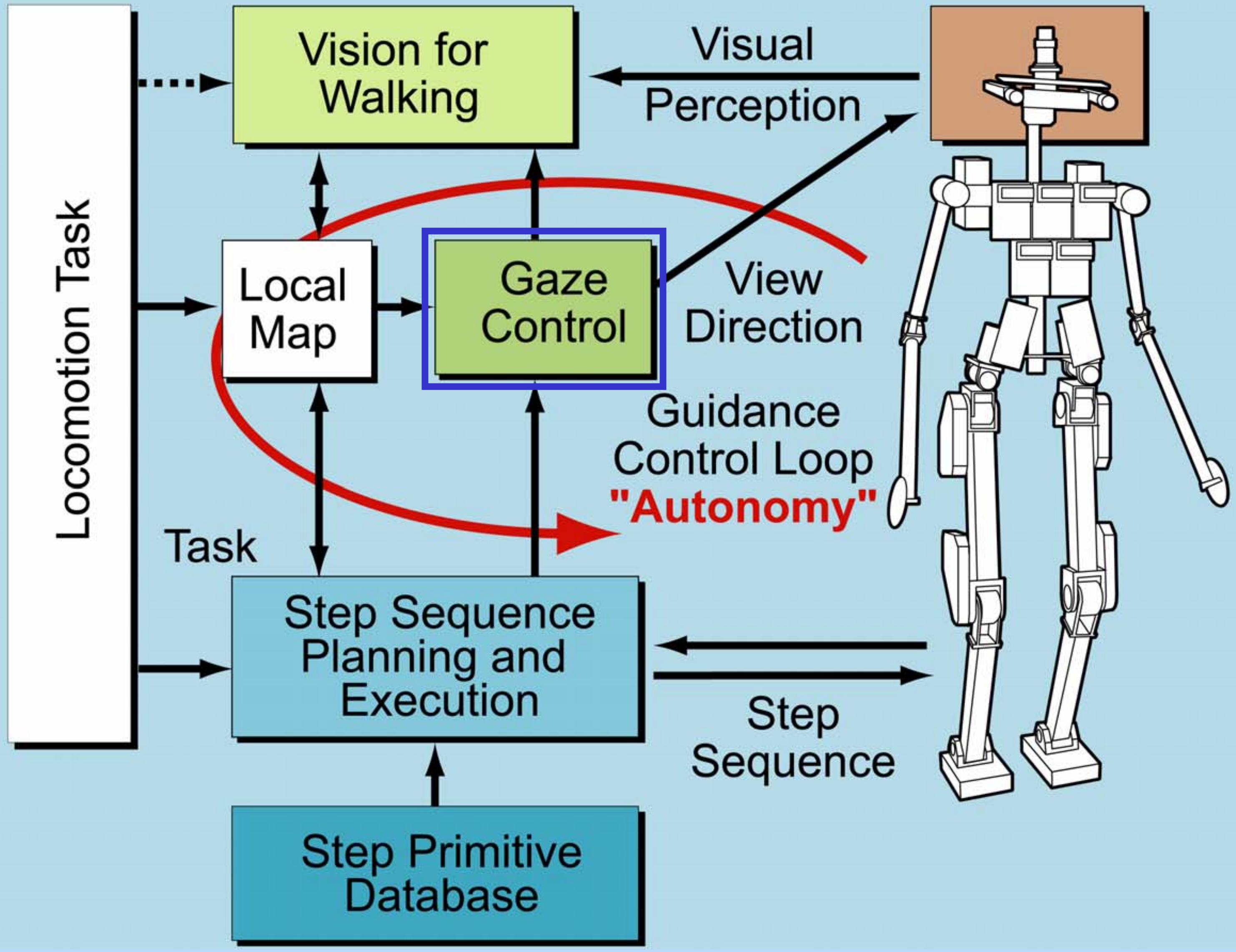
- For each 2D line - two hypotheses:
  - projection of a vertical 3D edge
  - projection of a horizontal 3D edge
- Orientation of the camera system relative to the gravity axis:
  - pruning of vertical edge hypotheses
  - orientation horizontal edges

Step 2

- Edge grouping ⇨ Cuboid Objects ⇩ **Stairs**



Selection
of Camera View Direction
= Gaze Control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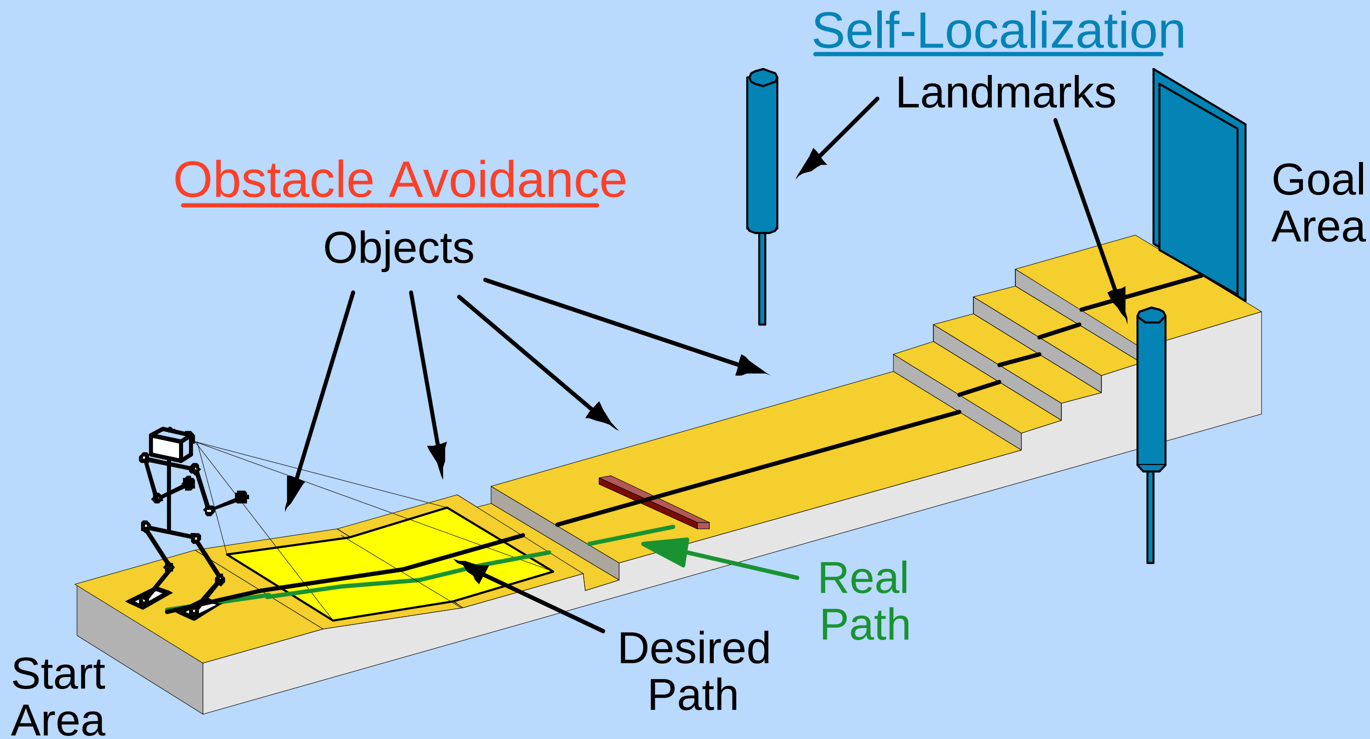
Intention Problem: "*Where and how to look next ?*":

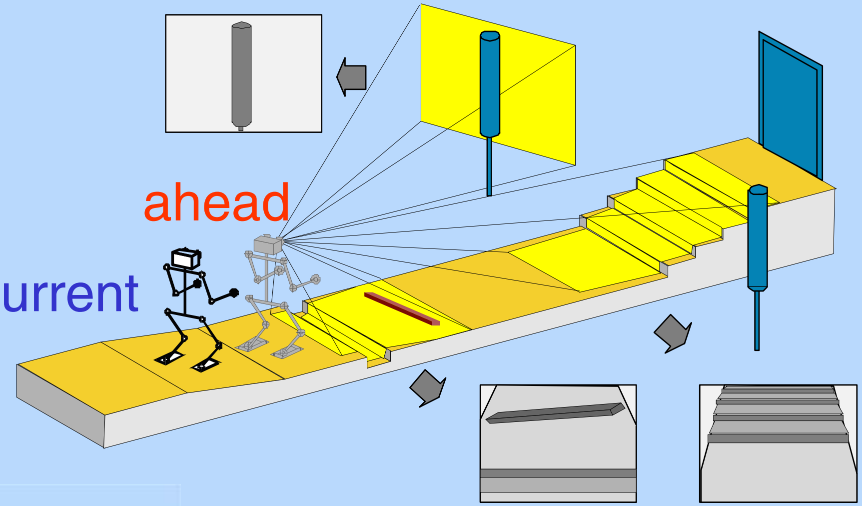
Cameras: + Limited Field of View
+ Active Vision System

⇒ Adaptation of View Direction



Bio-Inspired Approach:

Maximization of anticipated visual information content by selection of Ω: pan and tilt



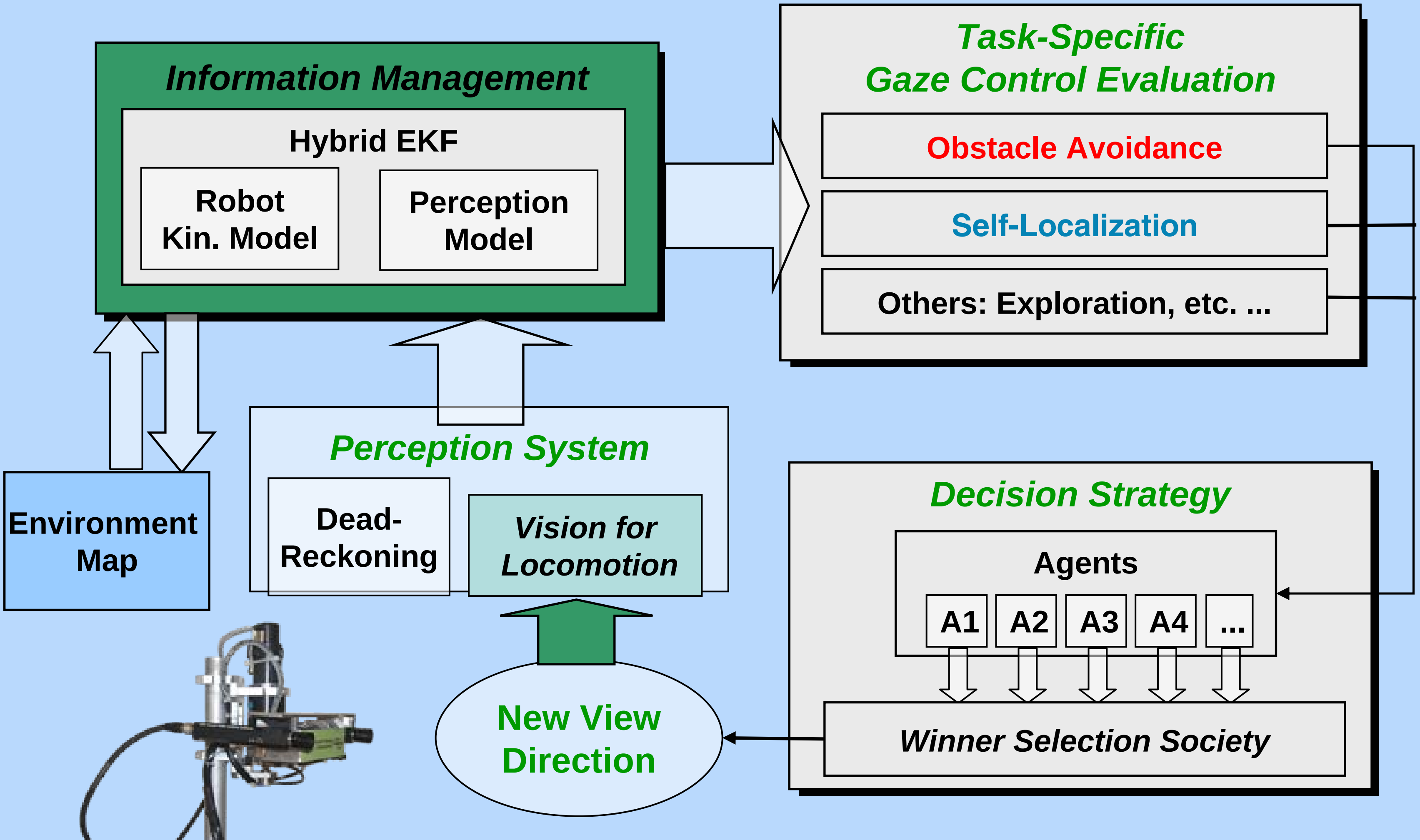
$$\widehat{\boldsymbol{\Omega}}_\star = \arg\max_{\widehat{\boldsymbol{\Omega}}} \sum_{i=1}^{N} \widehat{\mathcal{IC}}_i(\widehat{\boldsymbol{\Omega}}, {}_0\boldsymbol{x}_0, {}_F\boldsymbol{x}_i, \nu_i),$$

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

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

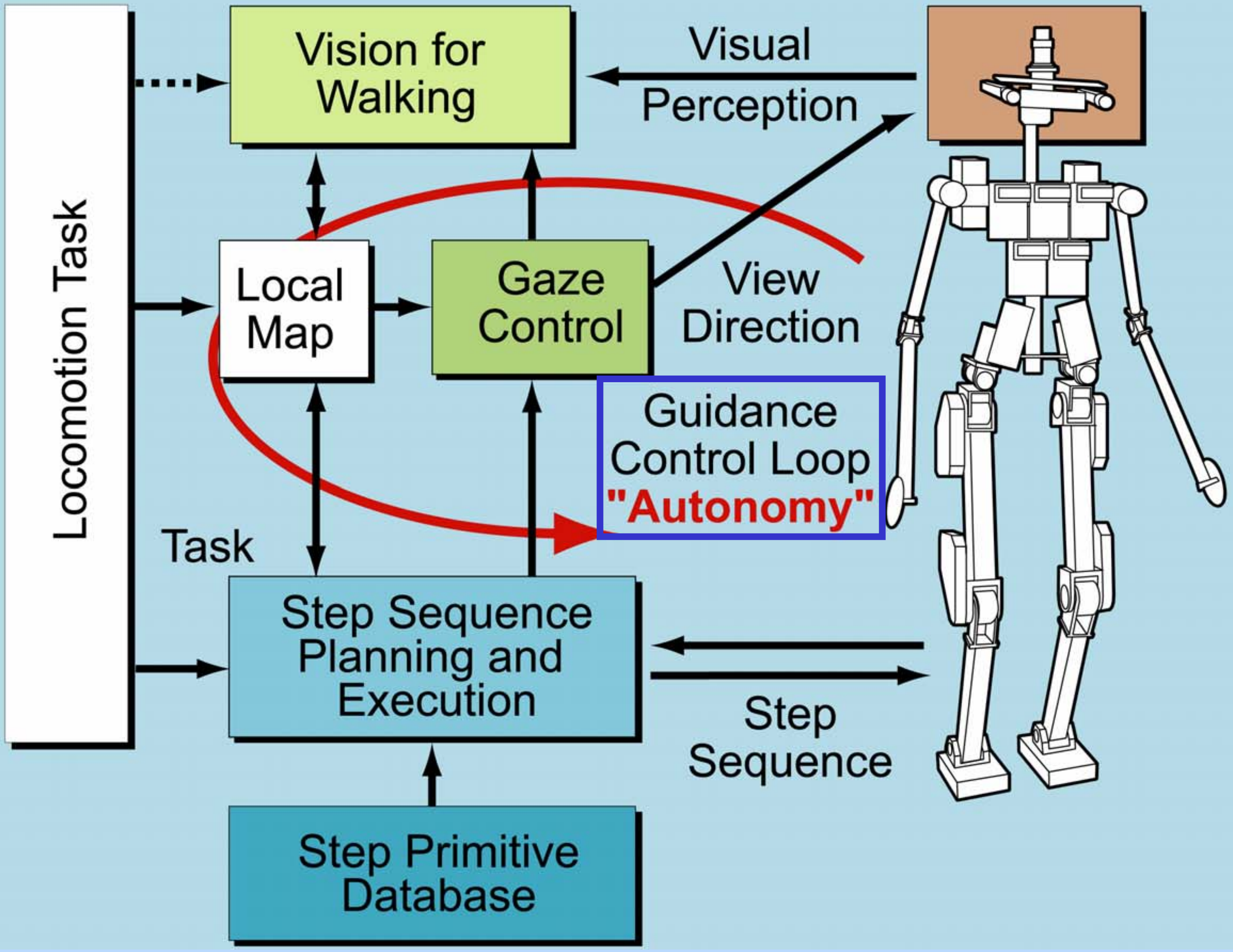
Information Content IC
Maximization
$\Downarrow$
Uncertainty
Minimisation

Selection of Appropriate 1-Step-Ahead View Direction

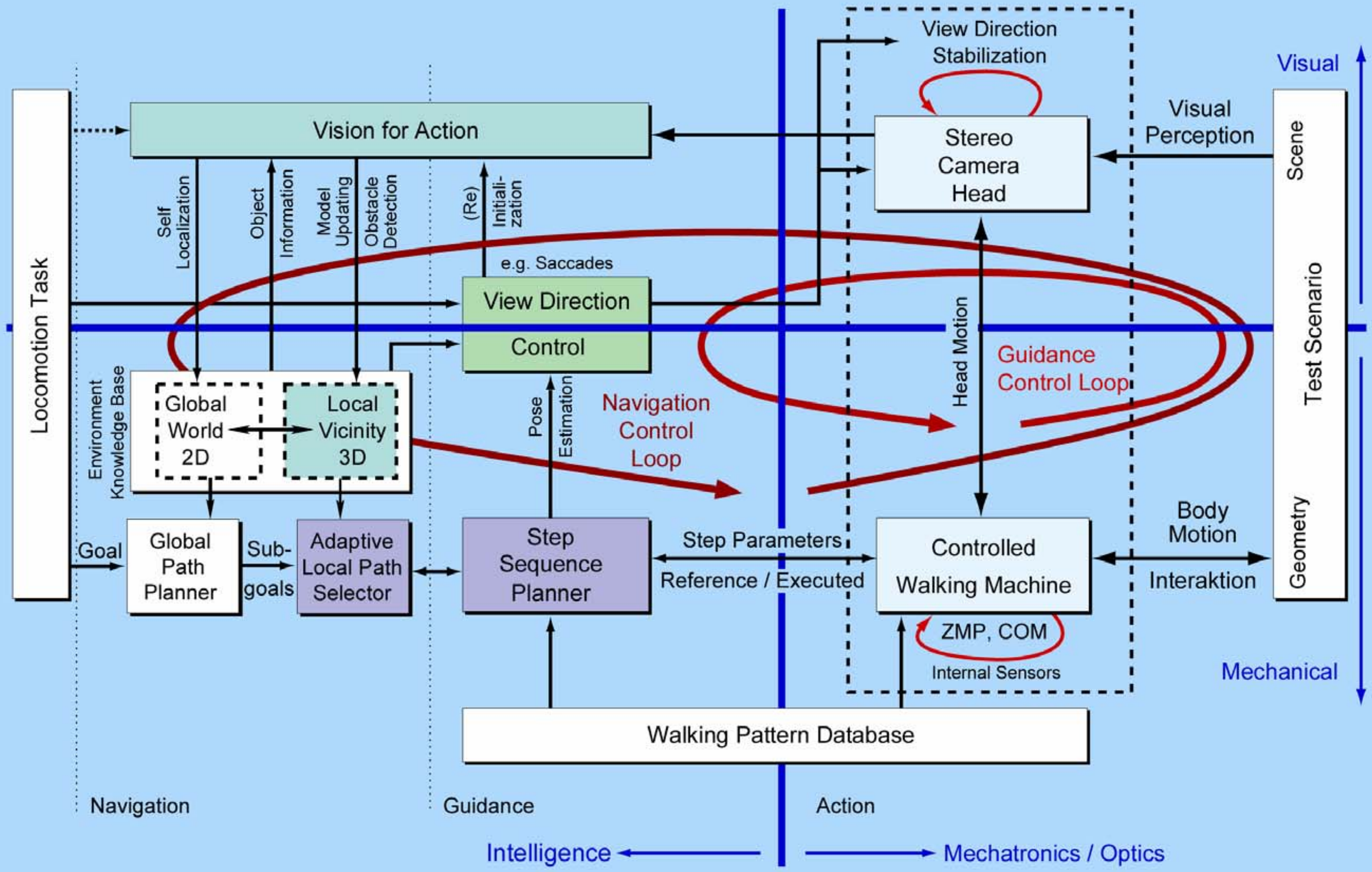


Architecture of Task- and Situation-Dependent Gaze Selection System

Locomotion Autonomy
by means of Perception
= Intelligent Walking



Autonomy through Visual Guidance



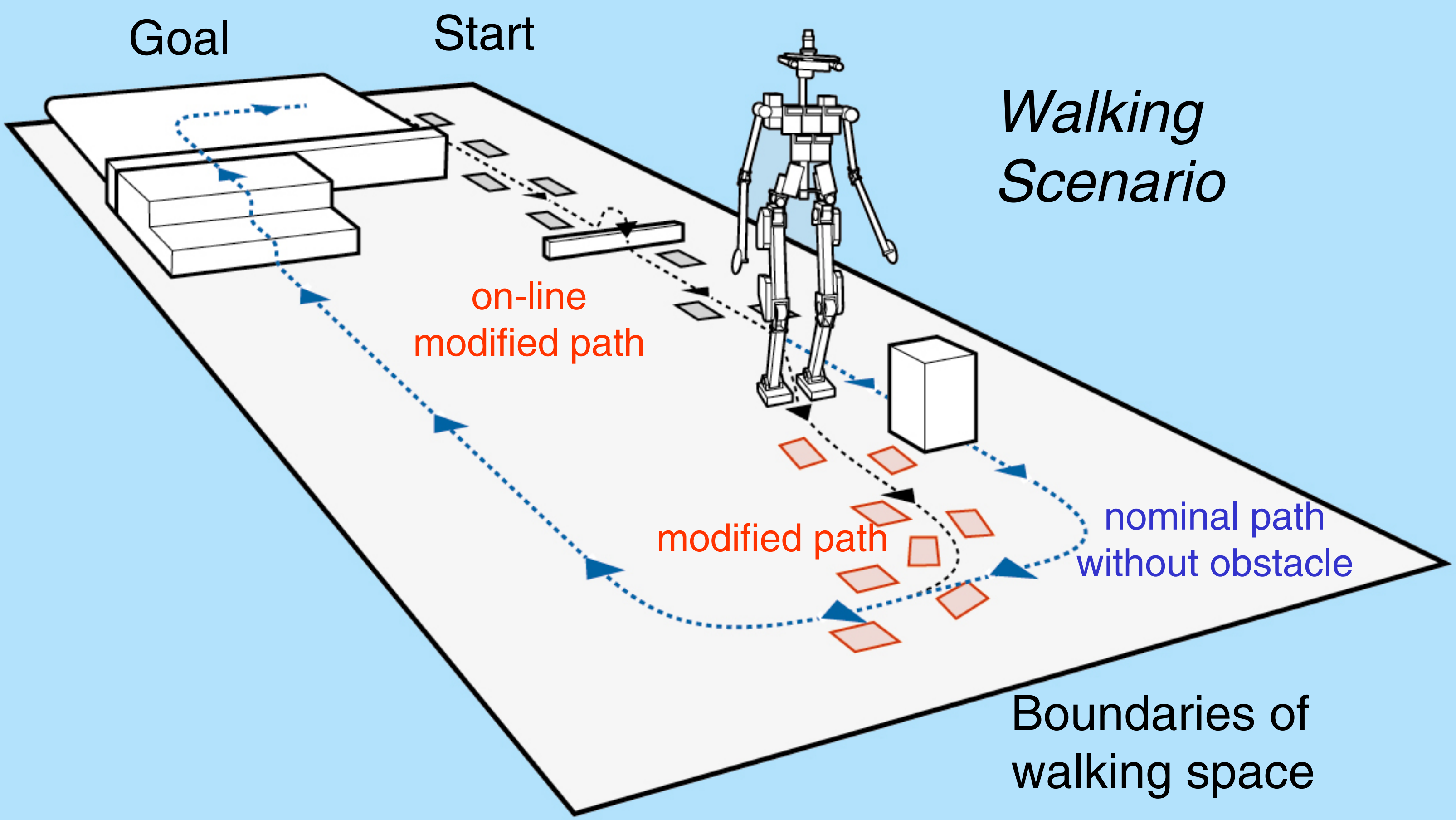
Bio-Inspired Guidance and Control Architecture

Presentation
Hannover Industrial Exhibition
April 2003

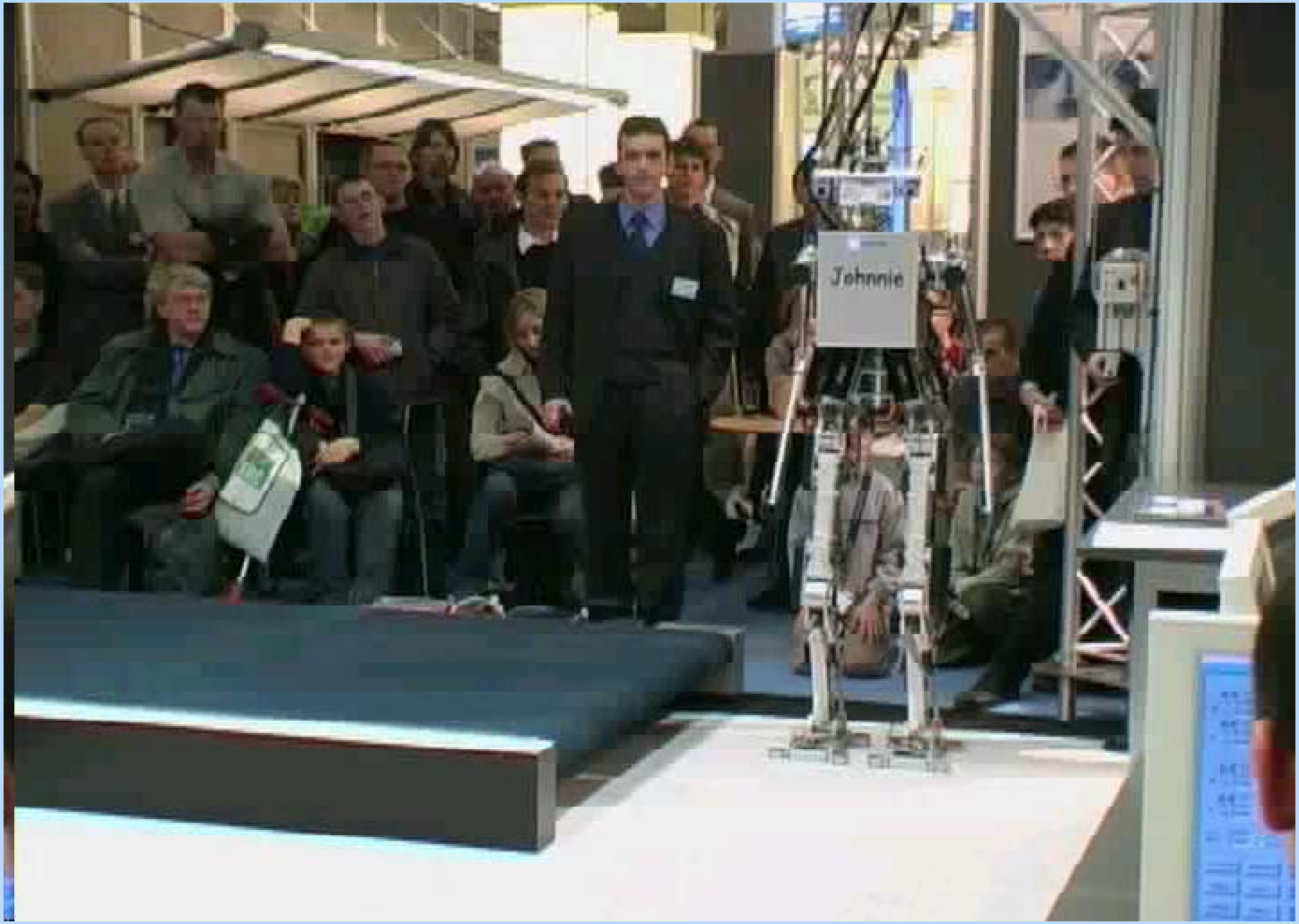
Cooperation Project

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

- Stabilized Walking Machine, Institute of Applied Mechanics, TU München



Locomotion Task: ”Walk along U-Shaped Path”


Johnnie

Concluding Remarks

- From teleoperated and preprogramed to semi-autonomous walking
- Improved qualitiy of locomotion by incorporation of artificial cognitive functionalities
- Inspiration by analysis of biological prototypes
- Spin-off: better understanding of certain aspects of locomotion autonomy in humans
- Underlining importance of research in the area of cognitive control methodologies with application to cognitive vehicles, robots, machines. . .