Perception-Based Humanoid Robot Walking
- From Automation to Autonomization

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Japan 2004
HONDA Asimo: It’s not so easy ......
Motivation

Basis of Locomotion Autonomy in Humans and Robots?

Intelligent Interplay of Perception and Locomotion: Cognitive Functionalities


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Vision Guided Walking Machine
Humanoid Robot in Pedestrian Walk Scenario
"The view anticipates the step"
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
Stabilized Biped Robot

Camera Head

Vision for Walking

Locomotion Task

Local Map

Gaze Control

Visual Perception

View Direction

Guidance Control Loop

"Autonomy"

Step Sequence Planning and Execution

Step Primitive Database

Task

Step Sequence

• On-line

• Off-line

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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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START → barrier → GOAL

trans $q_{l_1 \sim l_2}$

large obstacle
Step Primitive:

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Computation of Joint Torques for Step Primitive Data Base

= Step Sequence Planning – offline
3-Phase Optimization with Objectives:
Stability and Minimal Energy

Kinetic Robot Model
3 Locomotion Phases:

- pre-swing
- swing
- heel-contact

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

(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)
Step Sequence Generation by Bio-Inspired Approach

“3-Steps-Ahead-Strategy”

\[
l = \begin{cases} 
  d/3 & \text{for } 3.5 \, l_n \geq d > 2.5 \, l_n \\
  d/2 & \text{for } 2.5 \, l_n \geq d > 1.5 \, l_n \\
  d & \text{for } 1.5 \, l_n \geq d > 0.5 \, l_n 
\end{cases}
\]
Robot Vision for Autonomous Locomotion = Vision for Walking
Locomotion Task

Vision for Walking

Local Map

Gaze Control

Step Sequence Planning and Execution

Step Primitive Database

Visual Perception

View Direction

Guidance Control Loop "Autonomy"

Step Sequence
camera system
inclination sensor
joint encoders

kinematics of camera pose rel. to foot frame
dead reckoning

WALKING MACHINE

vision system

scene analysis

edge detection
edge map
line extraction
straight edges
object detection and localization
detected objects
object classification
3D objects in view

object pose estimation by object feature tracking

object base edge
precise object pose

Local Environment Map (LEM)

Architecture of Perception Approach

1 image / step
1 image / 33 ms

$F_T F(k)$

$3D$ objects in view

1 image / 33 ms

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Phase #1:
Line Extraction and Object Detection (= Segmentation)
Phase #2a: Obstacle Localisation and Feature Tracking

Stereo Vision + Kinematics (+ Inclination Sensor)
Intersection of projection rays of the left and right camera

visible base edge
Phase #2b: Obstacle Localisation and Feature Tracking

Stereo Vision + Kinematics (+ Inclination Sensor)
Intersection of projection rays of the left and right camera

Precise Localization by Real-Time 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

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**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

*Phase 3b:*
Obstacle Classification Detail, Cuboid Objects
Selection of Camera View Direction = Gaze Control
Intention Problem: “Where and how to look next?”:

Cameras: + Limited Field of View  
+ Active Vision System  
⇒ Adaptation of View Direction

Self-Localization
Landmarks
Goal Area

Obstacle Avoidance
Objects

Real Path
Desired Path
Start Area

Intelligent Gaze Control
Bio-Inspired Approach:

Maximization of anticipated visual information content by selection of $\Omega$: pan and tilt

$$\hat{\Omega}_* = \arg \max_{\Omega} \sum_{i=1}^{N} \hat{IC}_i(\hat{\Omega}, 0, x_0, F, x_i, \nu_i),$$

$$\hat{\Omega}_{\text{min}} \leq \hat{\Omega} \leq \hat{\Omega}_{\text{max}} \quad \text{and} \quad g(\hat{\Omega}) = 0,$$

Information Content IC

Maximization

Uncertainty

Minimisation

Selection of Appropriate 1-Step-Ahead View Direction
Decision Strategy

Task-Specific Gaze Control Evaluation

Obstacle Avoidance
Self-Localization
Others: Exploration, etc. ...

Perception System

Environment Map
Hybrid EKF
Robot Kin. Model
Perception Model
Dead-Reckoning
Vision for Locomotion
New View Direction

Information Management

Agents
A1 A2 A3 A4 ...
Winner Selection Society

Architecture of Task- and Situation-Dependent Gaze Selection System
Locomotion Autonomy by means of Perception = Intelligent Walking
Autonomy through Visual Guidance
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

Intelligent 3-D Walker Johnnie with TUM Visual Guidance System
Locomotion Task: "Walk along U-Shaped Path"
Autonomous Walking:
Obstacle Avoidance and Self-Localization
Concluding Remarks

• From teleoperated and preprogramed to semi-autonomous walking
• Improved quality 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. . .