Motion Control of the CyberWalk Platform

EU STREP
FP6-511092 project
(2005-2008)

www.cyberwalk-project.org

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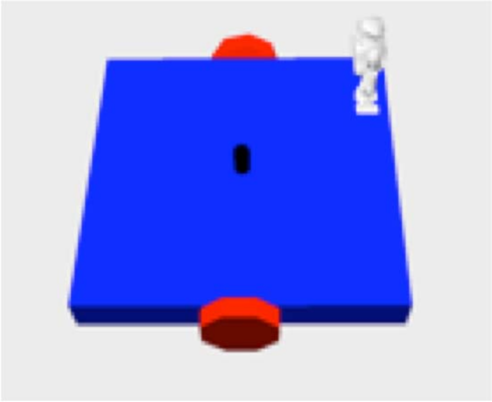
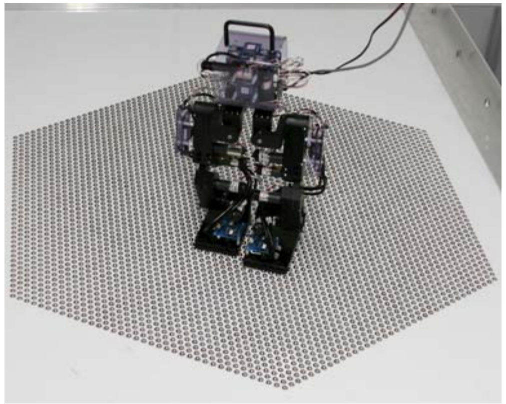
CyberWalk platforms

- ball-bearing
  - nonholonomic

simulation environment



small-scale CyberCarpet



- belt(-array)
  - omnidirectional

1D linear treadmill

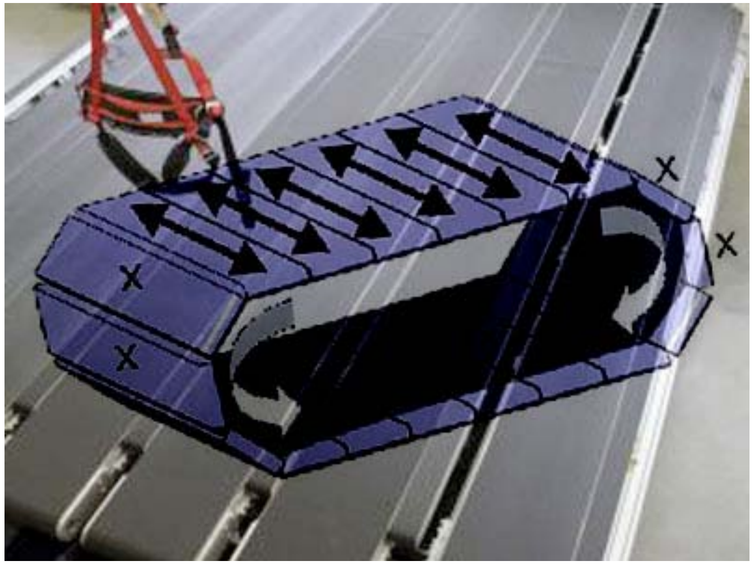
full-scale 2D platform

Control specifications

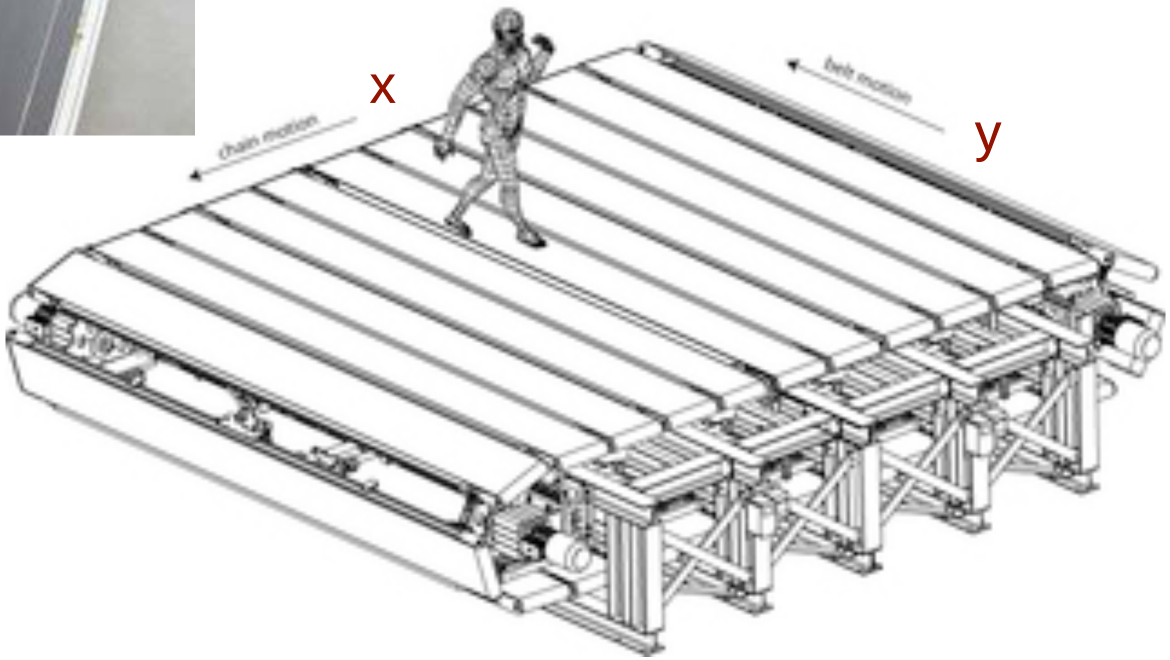
- keep the walker close to the platform center
  - taking into account platform dimensions
  - absolute orientation of walker is not relevant for VR
- satisfy user's perceptual/comfort constraints
  - smoothly controlled motion, especially during start/stop transients
- only measurement of walker position is available
  - visual feedback from external camera system
  - possibly, use also information on walker "orientation"
  - intentional walker motion (velocity/acceleration) is unknown
- interface/synchronize control commands with VR visualization

2D omnidirectional platform

mobility concept



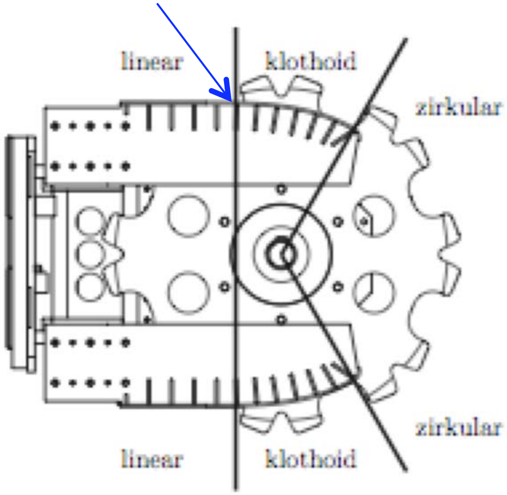
a chain moving in one direction (±x),
supporting 25 moving belts
in the orthogonal direction (±y)

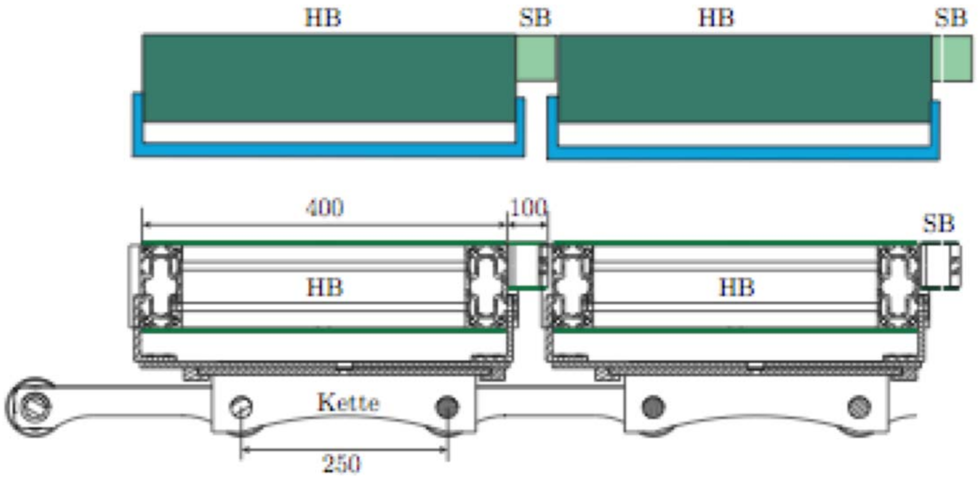


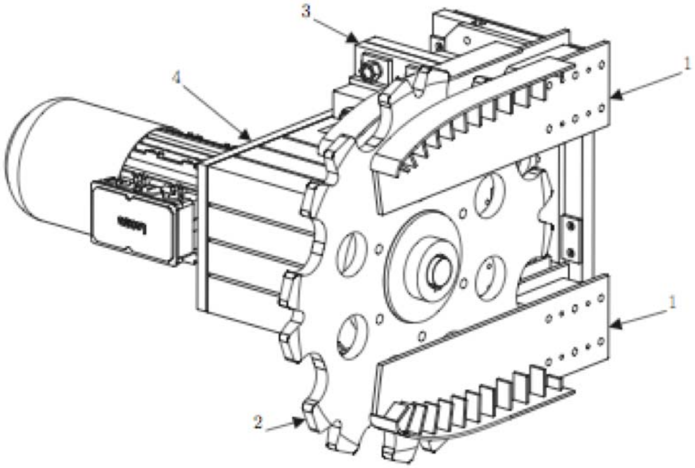
2D omnidirectional platform

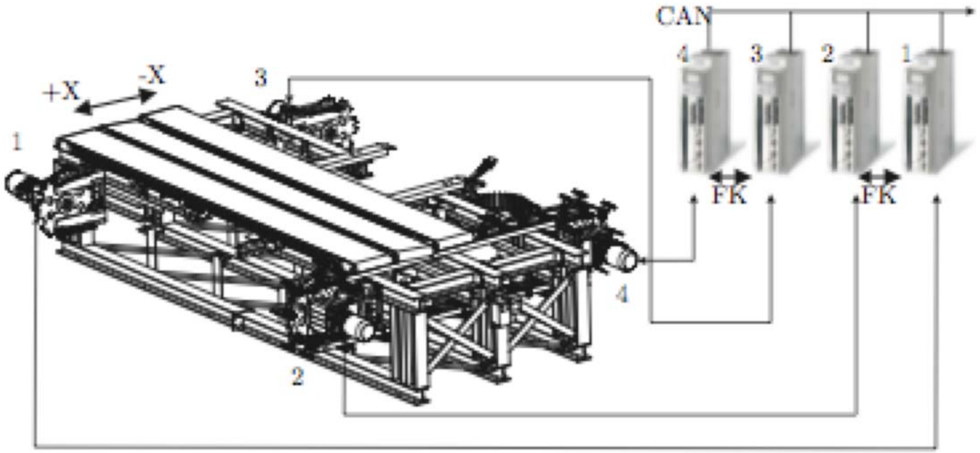
mechanical design and assembly of parts

continuous curvature profile





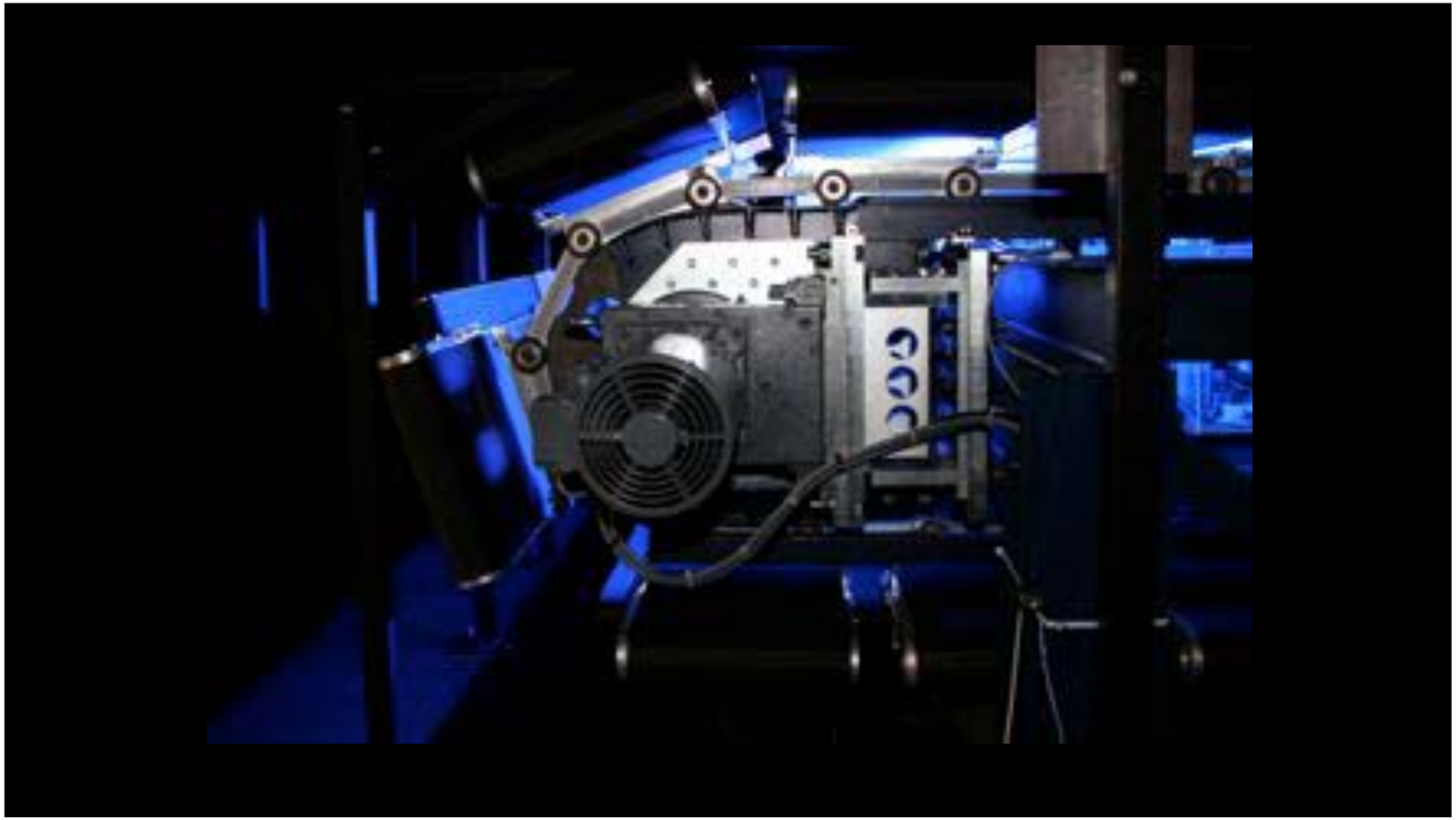




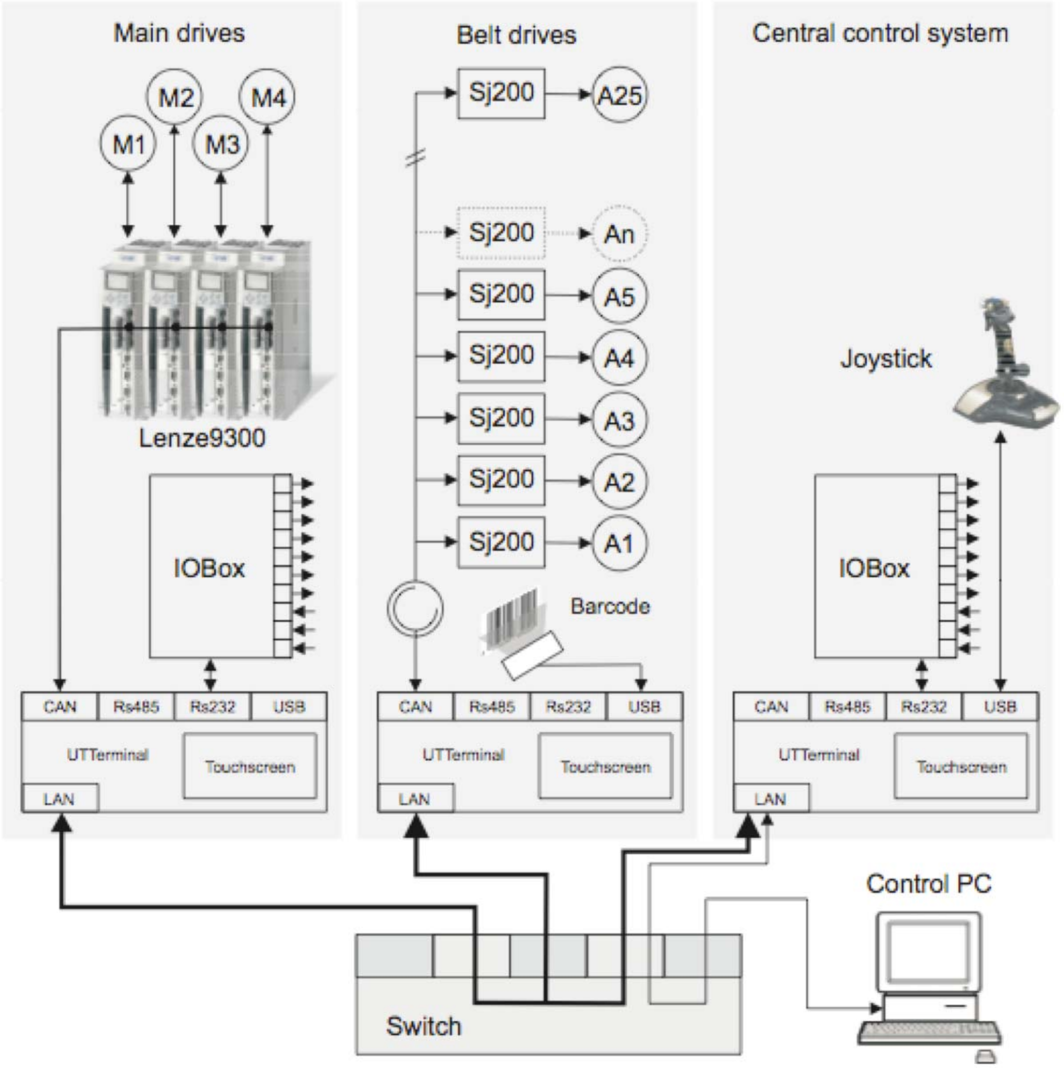
2D omnidirectional platform

assembly and electrical/hydraulic actuation

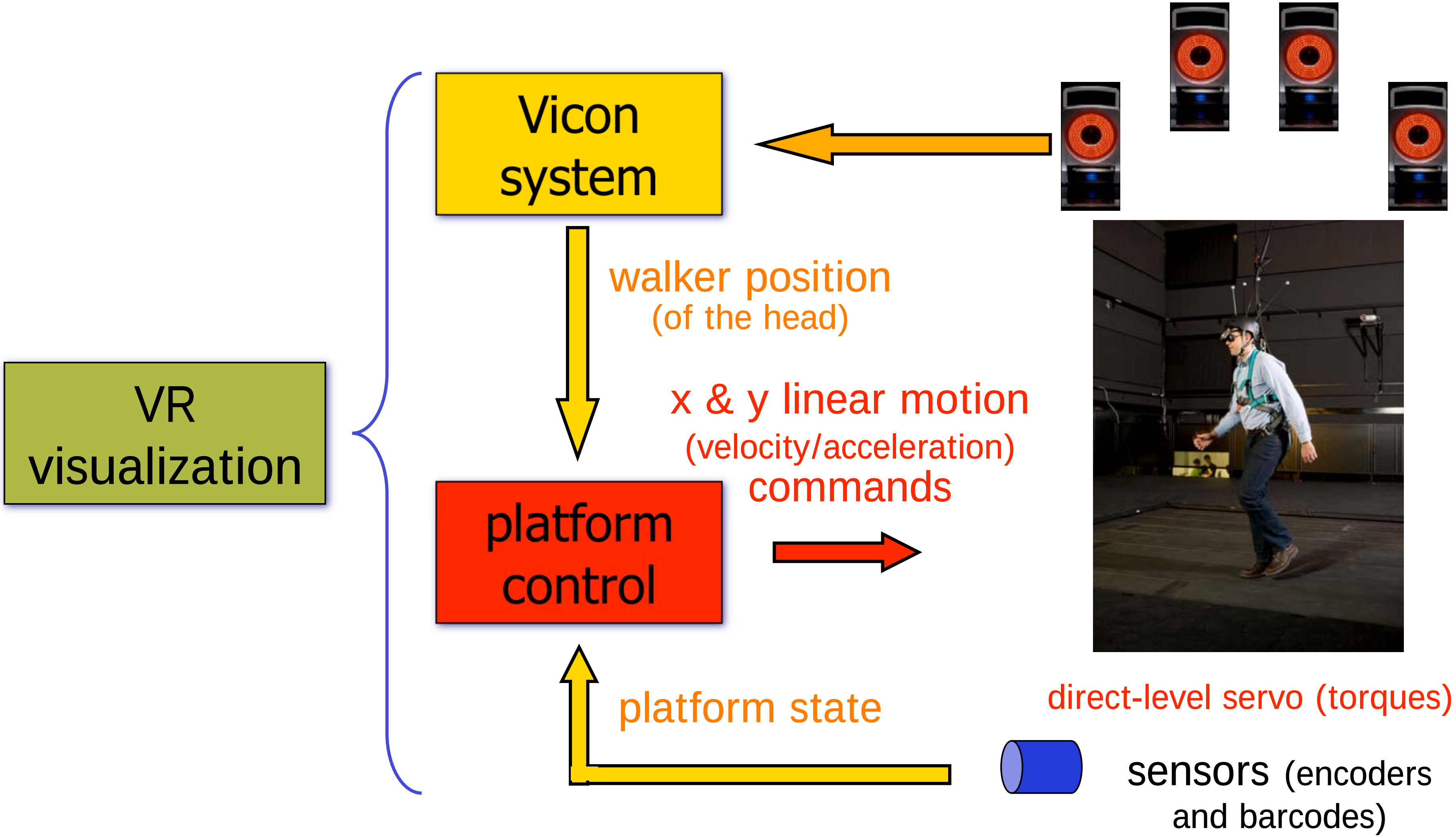
video



Control HW architecture



System architecture
2D omnidirectional platform



VR visualization

Vicon system

walker position
(of the head)

x & y linear motion
(velocity/acceleration)
commands

platform control

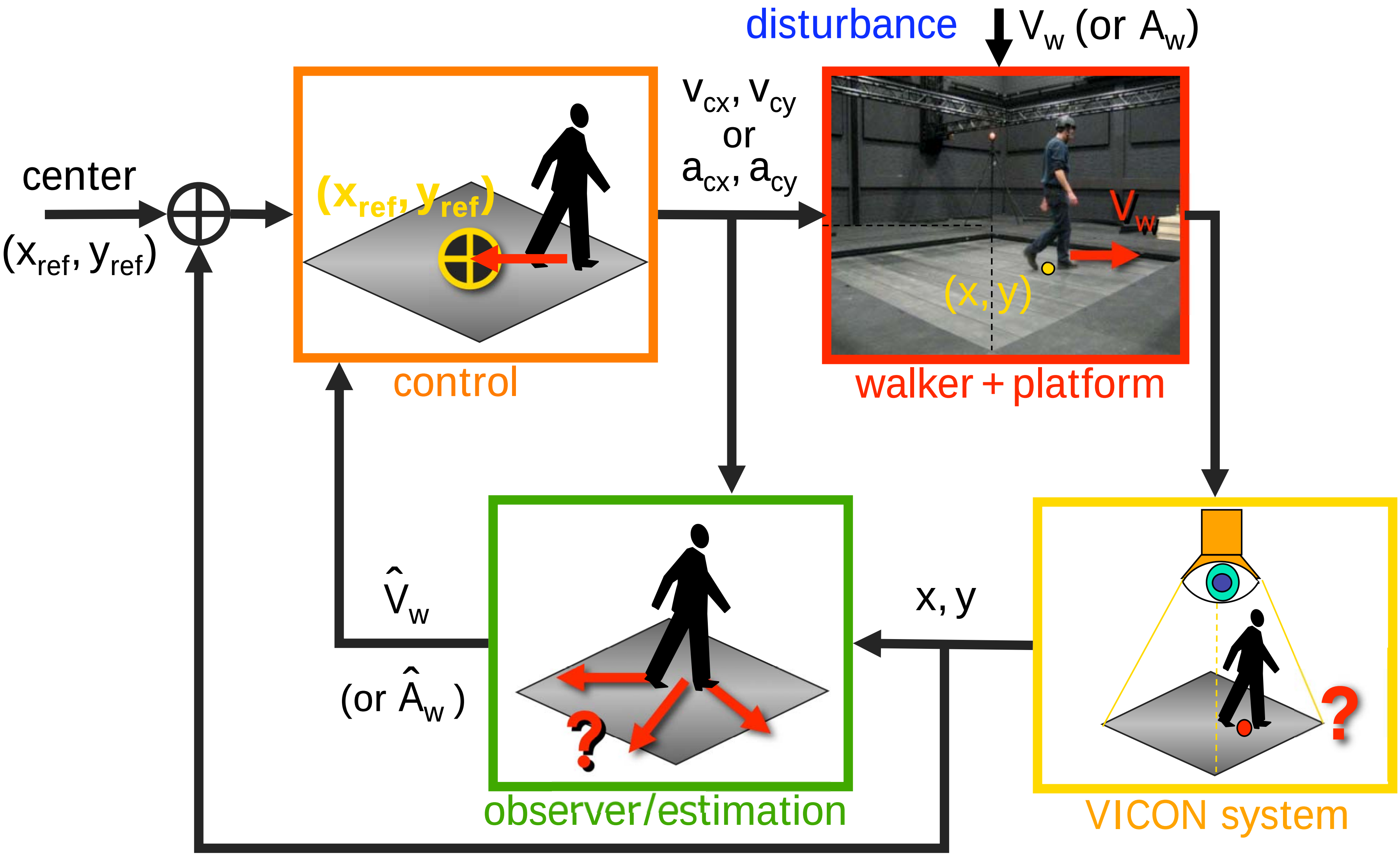
platform state

direct-level servo (torques)

sensors (encoders and barcodes)

Control principle

2D omnidirectional platform



Kinematic model

1D/2D omnidirectional platform

- second-order, linear, and decoupled model

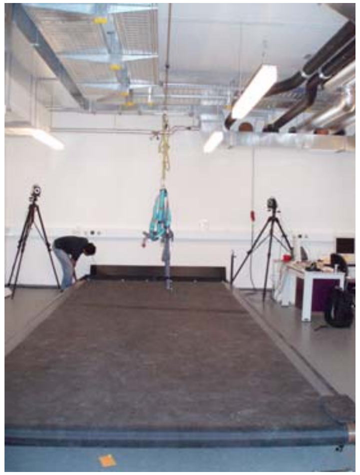
$$\boxed{\begin{aligned}\dot{x}_i &= v_i \\ \dot{v}_i &= a_{c_i} + a_{w_i}\end{aligned}}$$

- x_i absolute user position: measurable
- v_i absolute user velocity: not measurable
- a_{c_i} carpet acceleration: commanded
- a_{w_i} user acceleration: not measurable

  for each controlled direction $i = (x, y)$ (1D or 2D)

- applies directly also to the 1D linear treadmill…

2D



1D

Control design

1D/2D omnidirectional platform

- independent behavior in each direction ⟶ 1D analysis (drop index i)
- the nominal acceleration control law

$$a_c = -a_w - k_v v + k_x(\boxed{x_{ref}} - x)$$

reference position

yields a global, exponentially stable equilibrium at x_{ref}

- two separate estimators for walker acceleration a_w and velocity v

$$\begin{cases} \dot{\xi}_1 &= \xi_2 + k_1(x - \xi_1) \\ \dot{\xi}_2 &= a_c + k_2(x - \xi_1) \\ \hat{a}_w &= k_2(x - \xi_1) \end{cases}$$

“disturbance” observer

$$\begin{cases} \dot{\xi}_3 &= k_3(x - \xi_3) \\ \hat{v} &= k_3(x - \xi_3) \end{cases}$$

“dirty” derivative

provide (stable) low-pass filtered versions of the actual values

$$\hat{A}_w(s) = \frac{k_2}{s^2 + k_1 s + k_2} A_w(s) \qquad \hat{V}(s) = \frac{k_3}{s + k_3} V(s)$$

- actual feedback law

$$a_c = -\boxed{\hat{a}_w} - k_v \boxed{\hat{v}} + k_x(x_{ref} - x)$$

Modified position reference

1D/2D omnidirectional platform

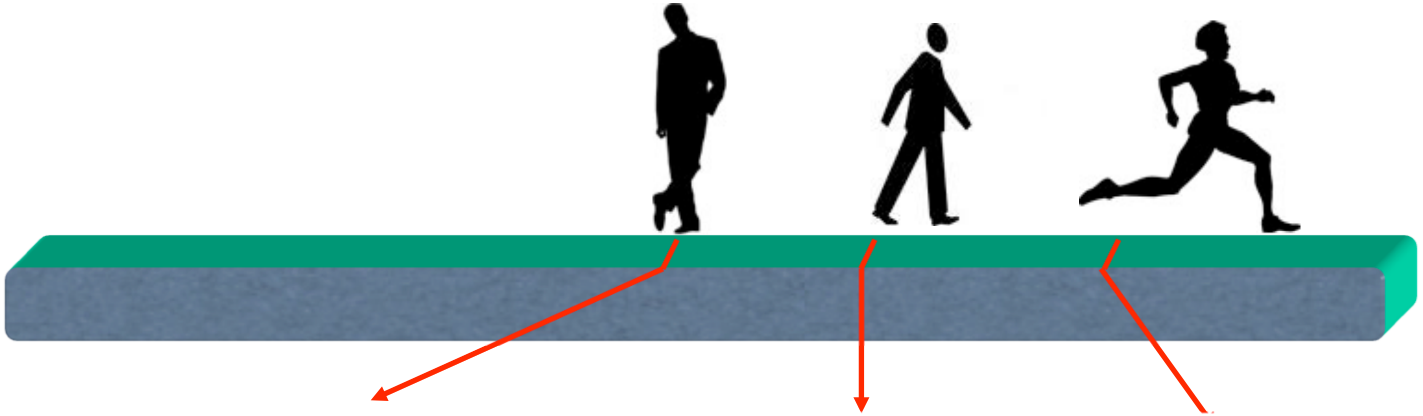
- a useful idea: modify x_{ref} according to the user own velocity

$$x_{ref} = s(\hat{v}_w) + x_{ref,0}$$

scaled “saturation” function
e.g. $k_{ref} \arctan \hat{v}_w$

indirect estimation
of walker velocity $\hat{v}_w = \hat{v} - v_c$

  - if the user moves forward/backward, x_{ref} “follows” in part this motion
  - when the user suddenly halts, more space is available to smoothly stop the platform motion



$x_{ref,0}$ for standing

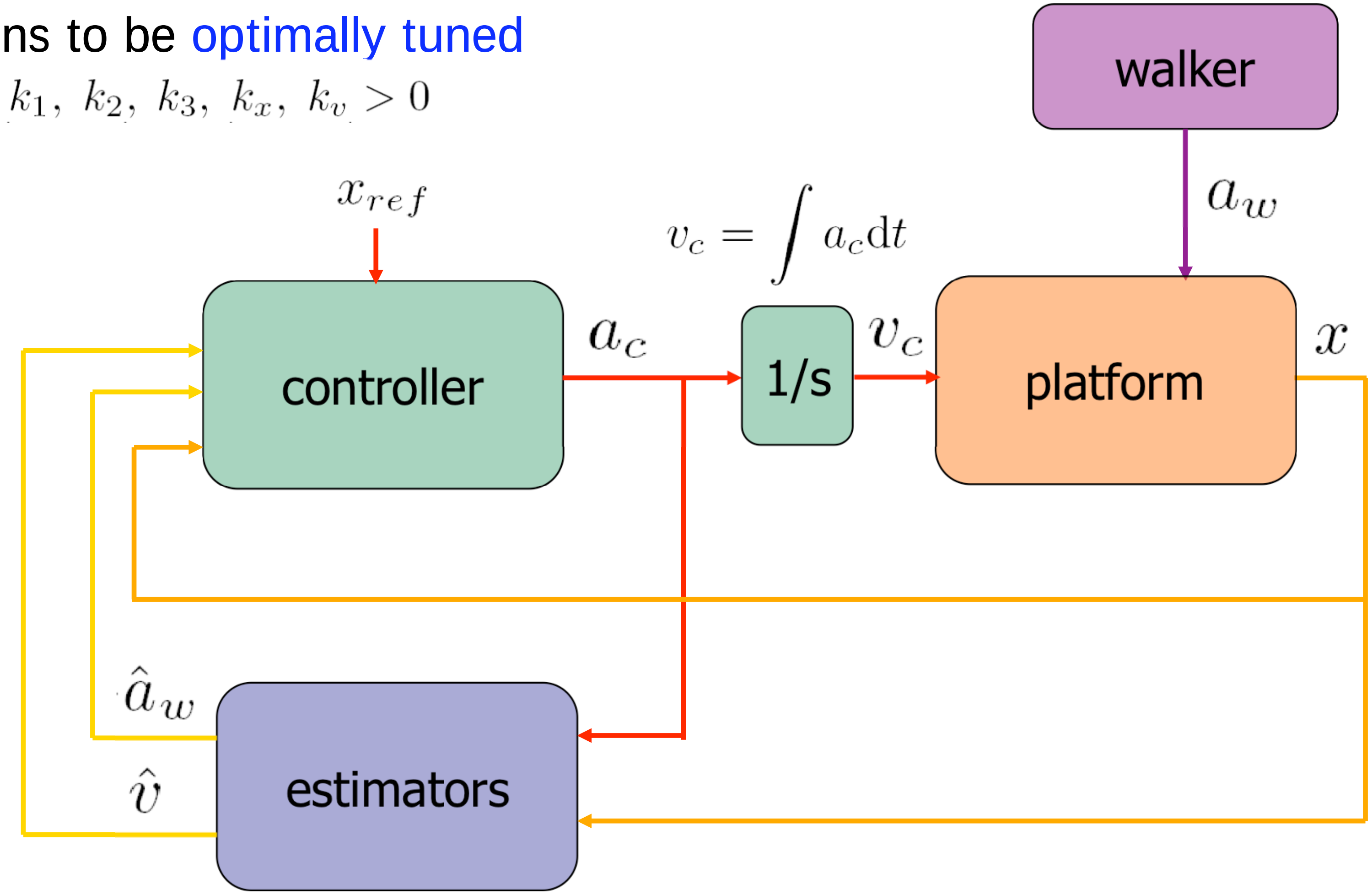
x_{ref} for walking

x_{ref} for running

Final control scheme
1D/2D omnidirectional platform

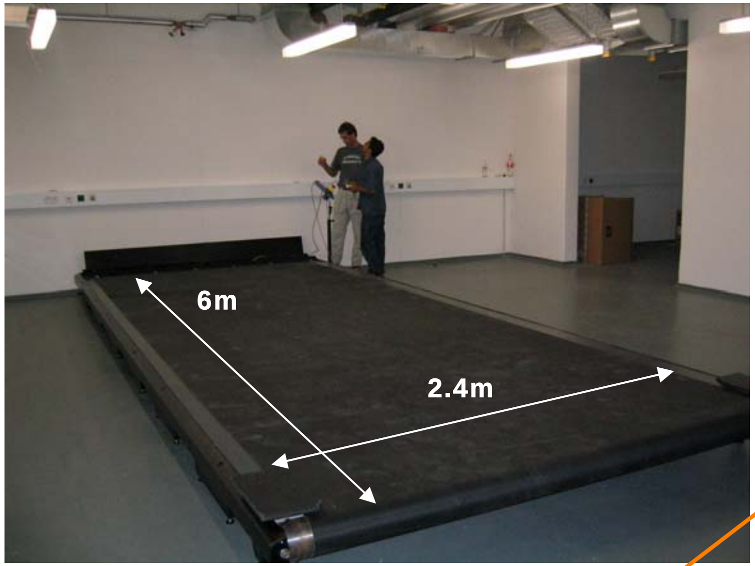
gains to be optimally tuned

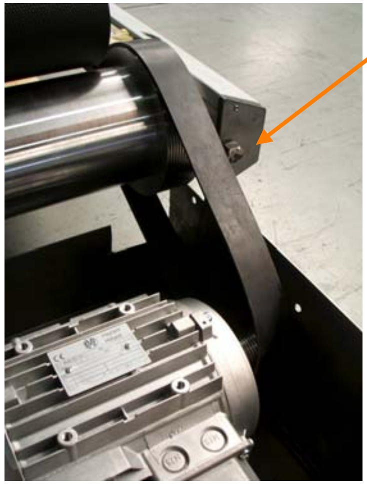
$k_1,\ k_2,\ k_3,\ k_x,\ k_v > 0$

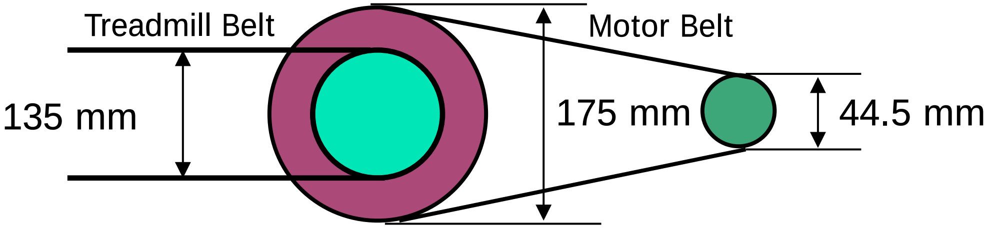


1D linear treadmill

electrical actuation and transmission







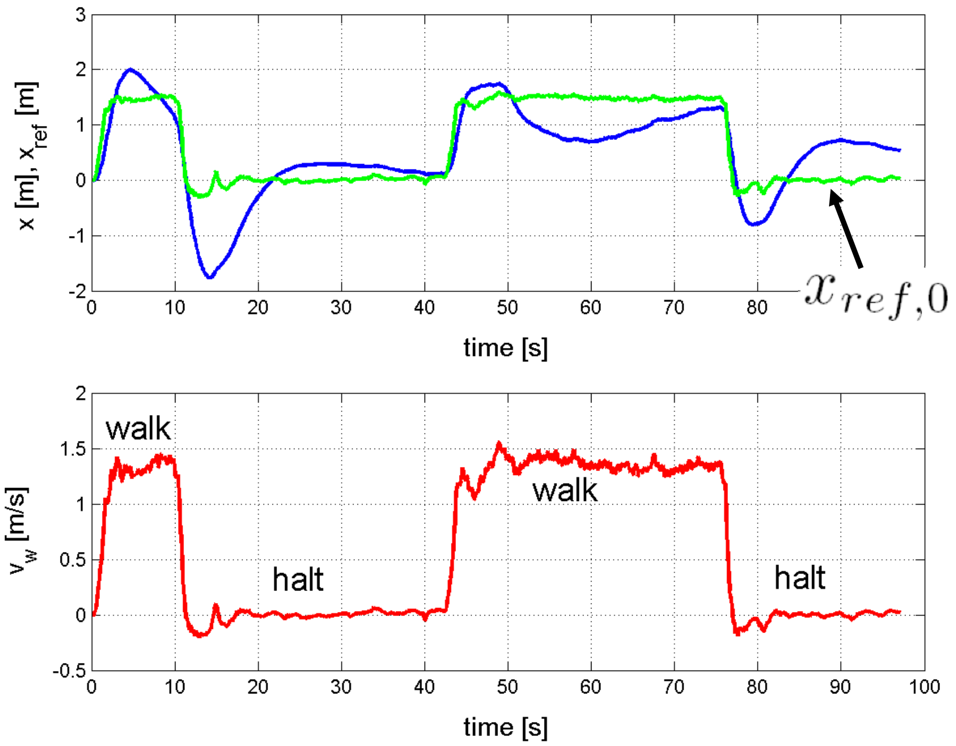
Experiments

1D linear treadmill

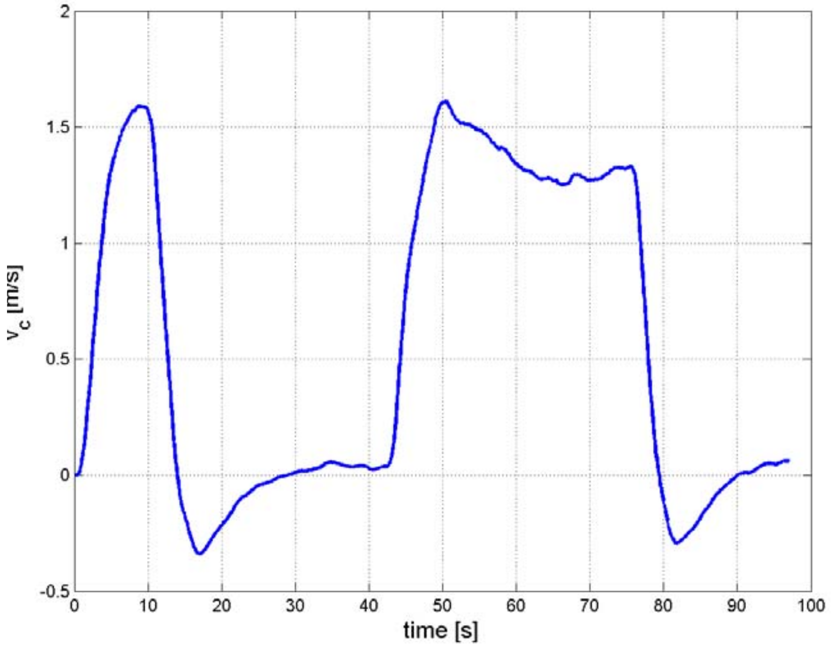
size: 6 m × 2.4 m

- max velocity: 40 km/h (s/w limited to 18)
- max acceleration: 3 m/s^2 (s/w limited to 1)
- s/w limited jerk to 1.5 m/s^3
- pose extraction via VICON at max data rate 120 Hz
- velocity commands data rate: 30 Hz
- different scenarios
  - standing still, but initially out of center
  - moving at constant speed/ halting in various combinations
  - accelerating/constant speed/ decelerating
  - random walk

Walk/halt/walk/halt



walker position, reference position,
and walker estimated velocity

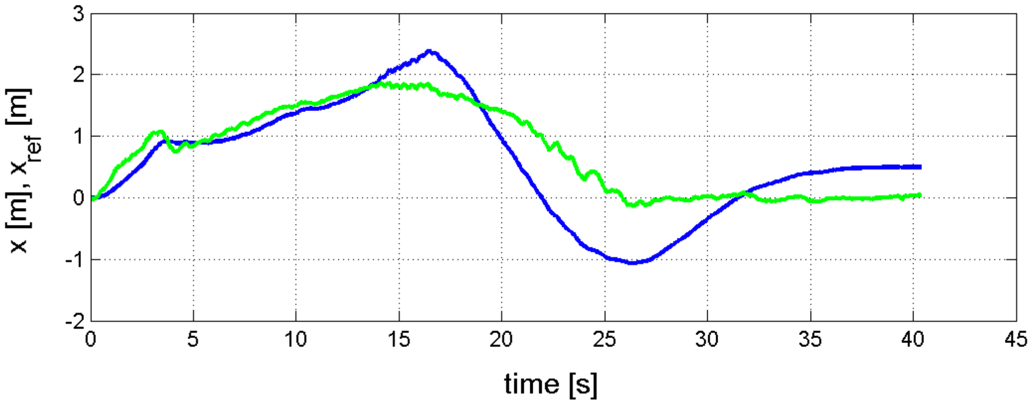


velocity command
sent to the carpet

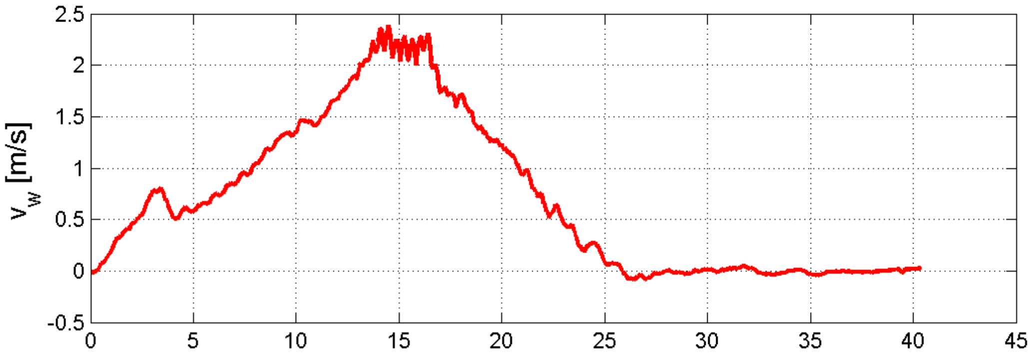
no velocity/acceleration jumps

ends with horizontal tangent
(zero acceleration)

Accelerate/decelerate



walker position and reference position



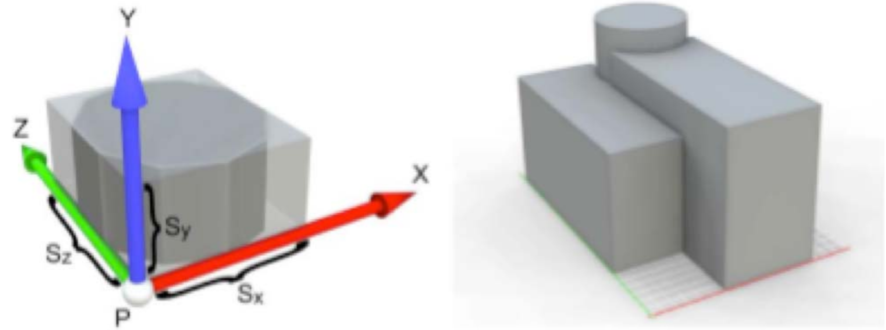
walker estimated velocity
(~ trapezoidal!)

Random walk

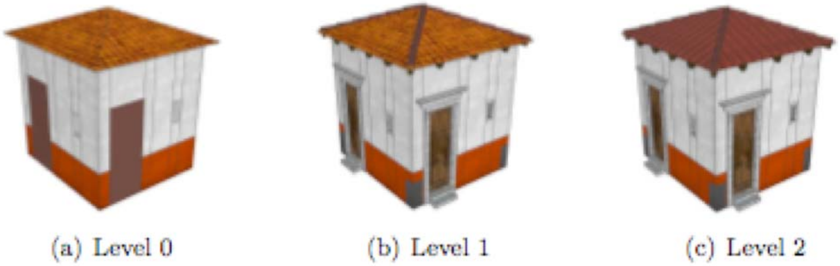
1D linear treadmill

video

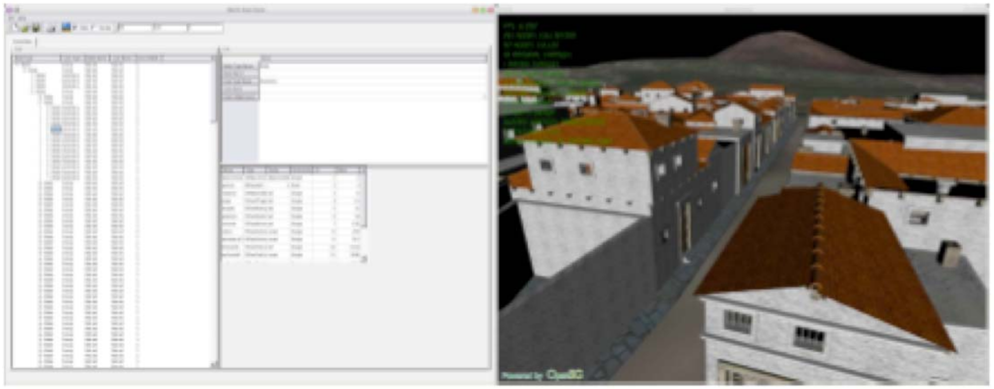
Virtual Reality: City Engine



architectural procedural language


(a) Level 0
(b) Level 1
(c) Level 2

levels of detail in rendering



Ancient Pompeii for CyberWalk

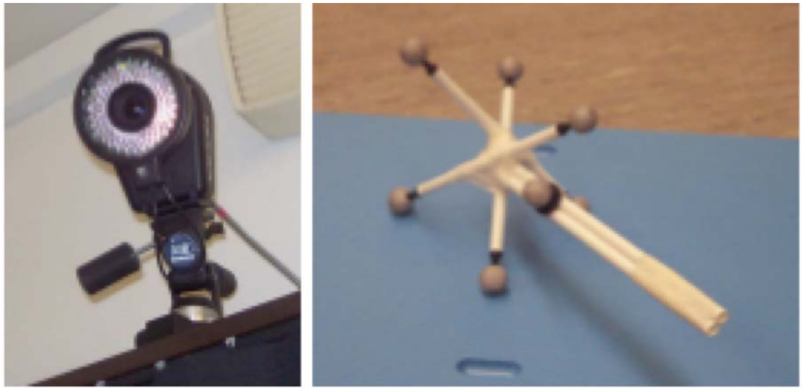
Rome rebuilt in one day!

Head Mounted Display

eMagin Z800 HMD
cost: 1500 US$,
weight: 2.7 kg

HMD (with tracker)

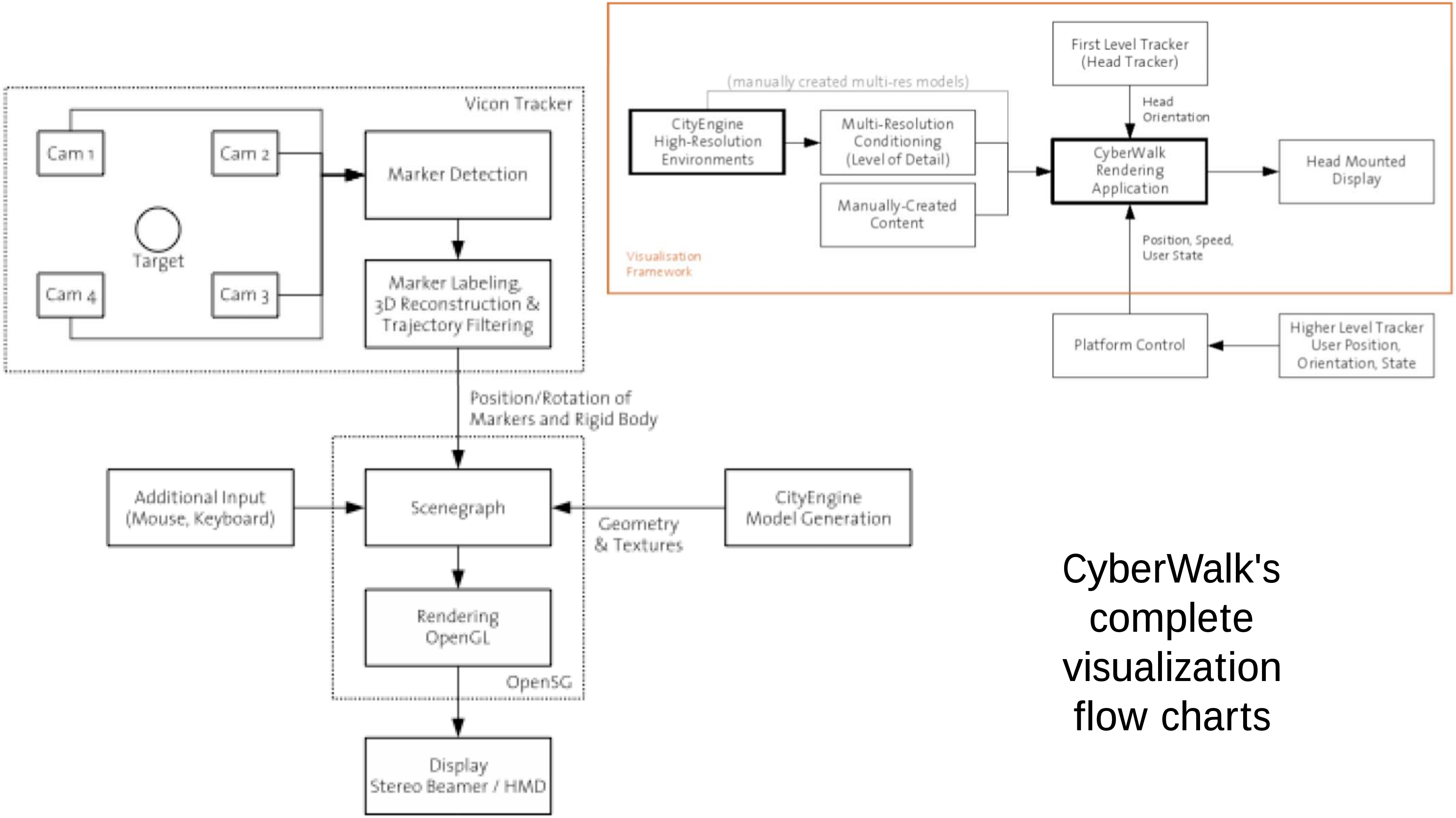
Walker tracking by Vicon



Vicon 8i optical tracker
(4 cameras)
accuracy: 1 mm/0.1 deg
frequency: >120 Hz
cost: 45000 €

emulating the tracked device

Integration with VR visualization



CyberWalk's complete visualization flow charts

Integration test

walker tracking, treadmill control, VR visualization

CyberWalk Integration Test
Tracking - Virtual Environment

Simon Haegler, ETH Zurich

Thanks to:
Jan Souman, Ilja Frissen, MPG Tuebingen
Paolo Robuffo Giordano, UOR

May 2007

video

Steps in control validation

for "kinematic control" of any platform

1. control design in the ideal case
   - commanded = actual velocities of platform (no dynamics)
   - no saturations in platform acceleration/jerk
2. trial control gains obtained via simulation on ideal model
3. experimental tests and collection of plant measures/data under closed-loop control of platform
4. platform dynamic model identification and fitting
5. model validation by matching new experimental data
6. set actual control gains via simulation on identified model and keeping perceptual constraints into account

finally, fine tuning on real platform + performance evaluation

Design steps 1 & 2

applied, e.g., to the 1D linear treadmill

design in the ideal case & choice of trial control gains

- (linearized) closed-loop system, with transfer function from walker's intentional acceleration (disturbance) to walker position (output to be controlled)

$$\boxed{X(s)} = \frac{(s+k_3)(s^3+(k_1+k_x k_{ref})s^2+k_x k_{ref} k_1 s + k_x k_{ref} k_2)}{s(D_1(s)+D_2(s))} A_w(s) = P(s)\boxed{A_w(s)}$$

$$D_1(s) = s^5 + (k_3+k_1+k_x k_{ref})s^4 + (k_v k_3 + k_3 k_1 + k_x + k_2 + k_x k_{ref} k_1)s^3$$

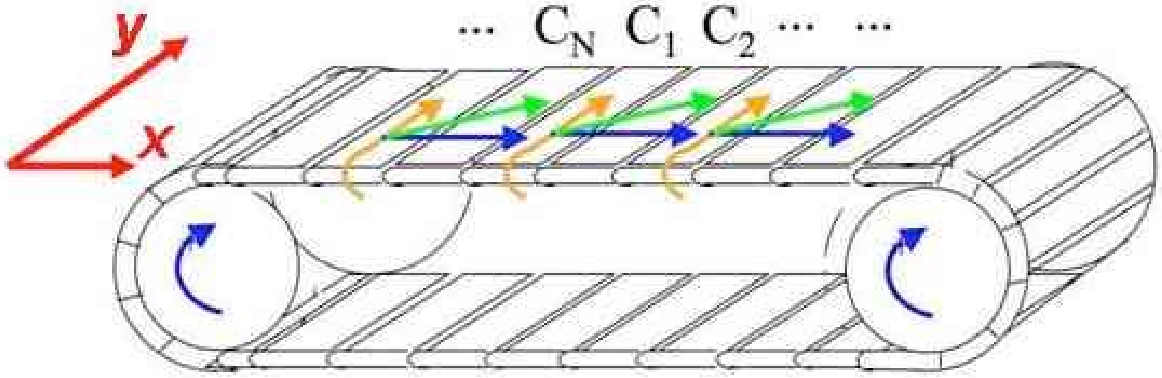
$$D_2(s) = (k_x k_3 + k_3 k_2 + k_v k_3 k_1 + k_x k_1 + k_x k_{ref} k_2)s^2 + (k_x k_2 + k_x k_3 k_1 + k_v k_3 k_2)s + k_x k_3 k_2$$

- control gains chosen so as to have stability and only real poles/zeros (≈ no oscillating transients)

$$P(s) = \frac{(\mathrm{s}+10.09)\,(\mathrm{s}+8)\,(\mathrm{s}+1.171)\,(\mathrm{s}+0.6465)}{\mathrm{s}\,(\mathrm{s}+9.583)\,(\mathrm{s}+5.983)\,(\mathrm{s}+3.323)\,(\mathrm{s}+0.6035)\,(\mathrm{s}+0.4174)}$$

Unmodeled dynamics

2D omnidirectional platform



(N = 25)

not critical in y direction (up to 50 Hz ≈ 300 rad/s, $\frac{V_c(s)}{V_{cmd}(s)} = 1$ is ok)

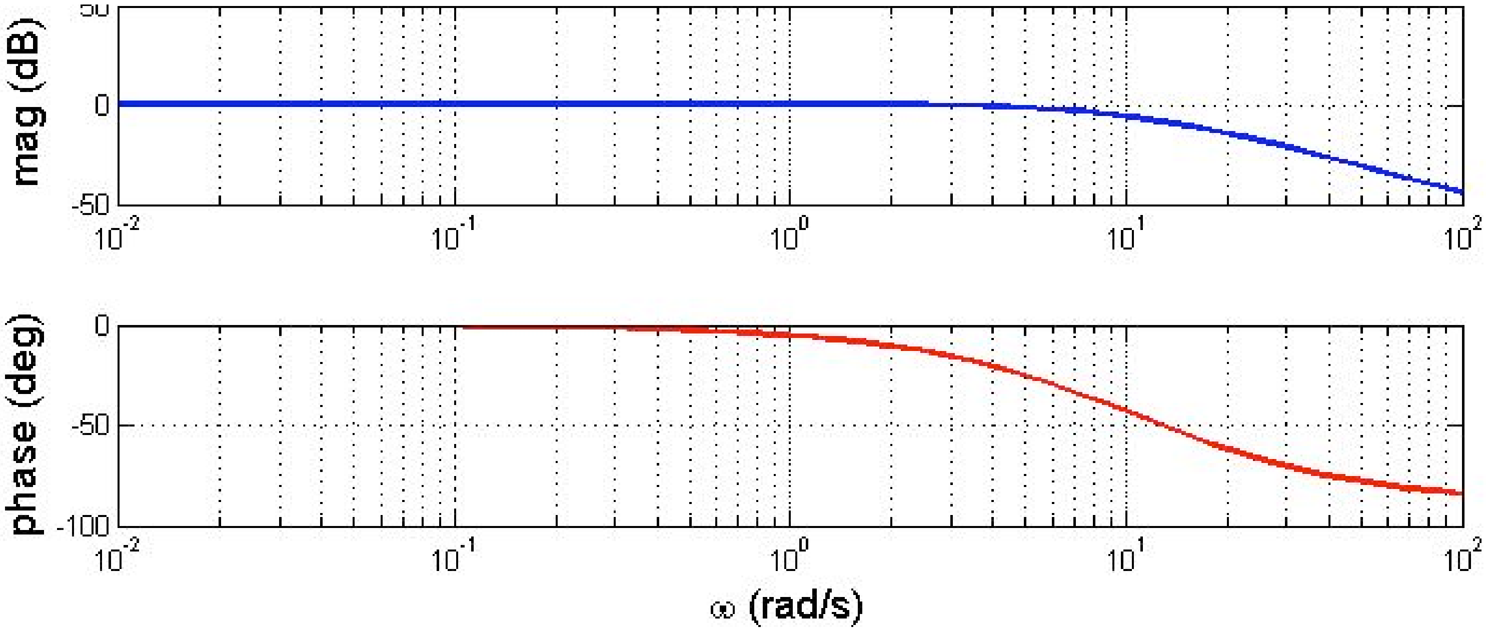
needs identification in x direction, due to the larger inertia

Design steps 3 & 4

2D omnidirectional platform

measures from experimental tests under closed-loop control
& dynamic model identification (only in x direction)

$$\frac{V_c(s)}{V_{cmd}(s)} = 1 \quad \Rightarrow \quad \frac{V_c(s)}{V_{cmd}(s)} = \frac{1.0275}{1 + 0.093967\,s}$$

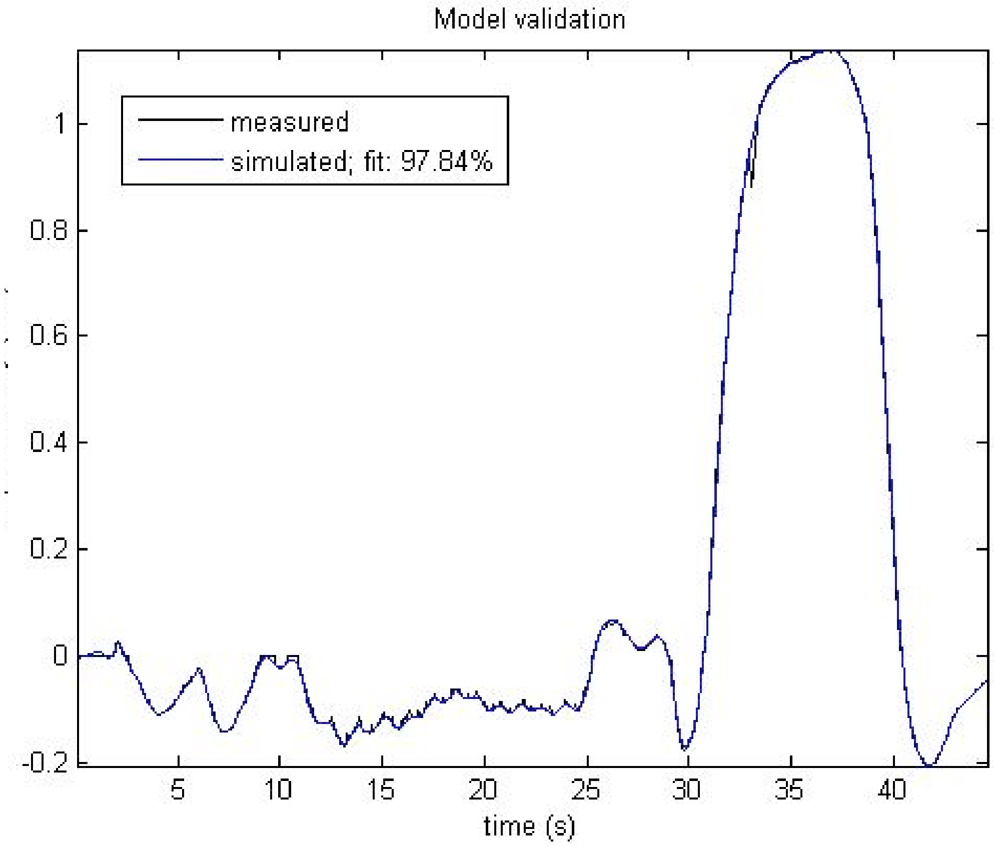


using *pem* function in Matlab System Identification Toolbox
(prediction error estimate for parametric linear models)

Design step 5

2D omnidirectional platform

model validation by matching new experimental data



$$\frac{V_c(s)}{V_{cmd}(s)} = \frac{1.0275}{1+0.093967\,s}$$

- other real platform motions vs. control simulations with identified model
- comparison of samples in time domain
- in all validation tests, fit was ≥ 91%

Design step 6

omnidirectional platform

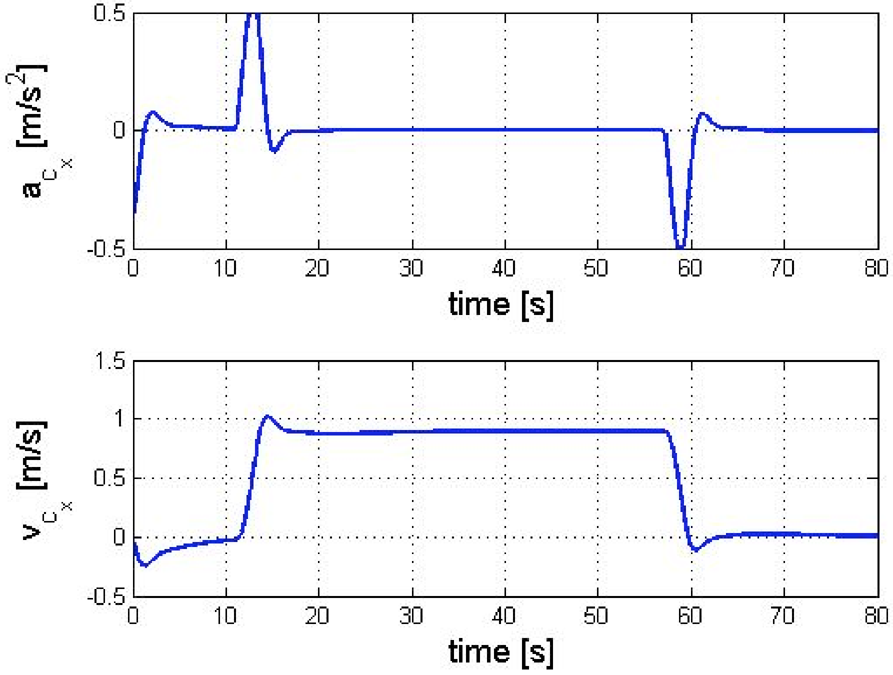
set actual control gains, with perceptual constraints

$$k_1 = 1, \quad k_2 = 0.2, \quad k_3 = 2.5, \quad k_x = 0.3, \quad k_{ref} = 1.6 \cdot \frac{2}{\pi}, \quad k_v = 1.5.$$

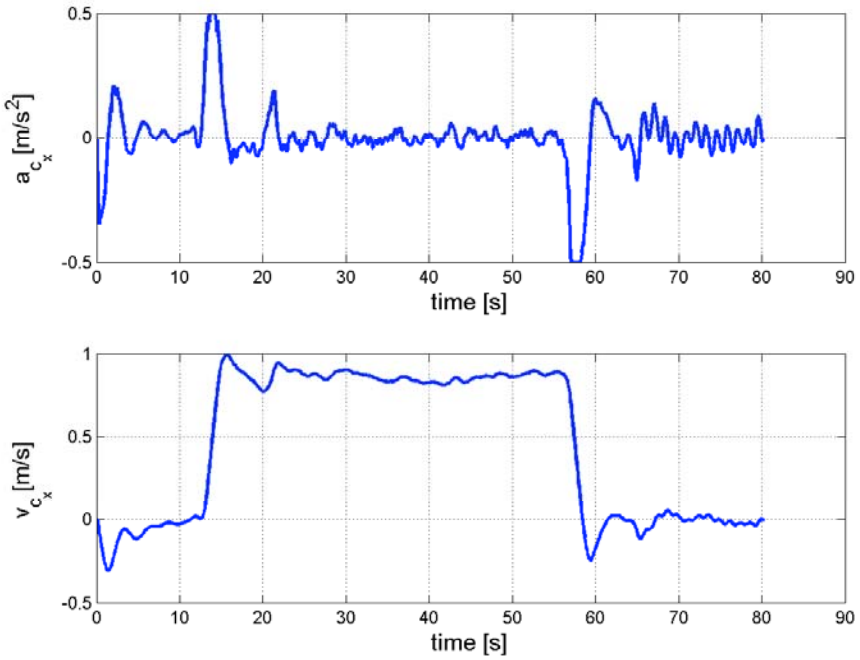
max acceleration = 0.5 m/s^2

max jerk = 1.2 m/s^3

simulation



experiment



walker starting off-origin, moving with constant velocity, and stopping

Need of tuning in 2D ...

video

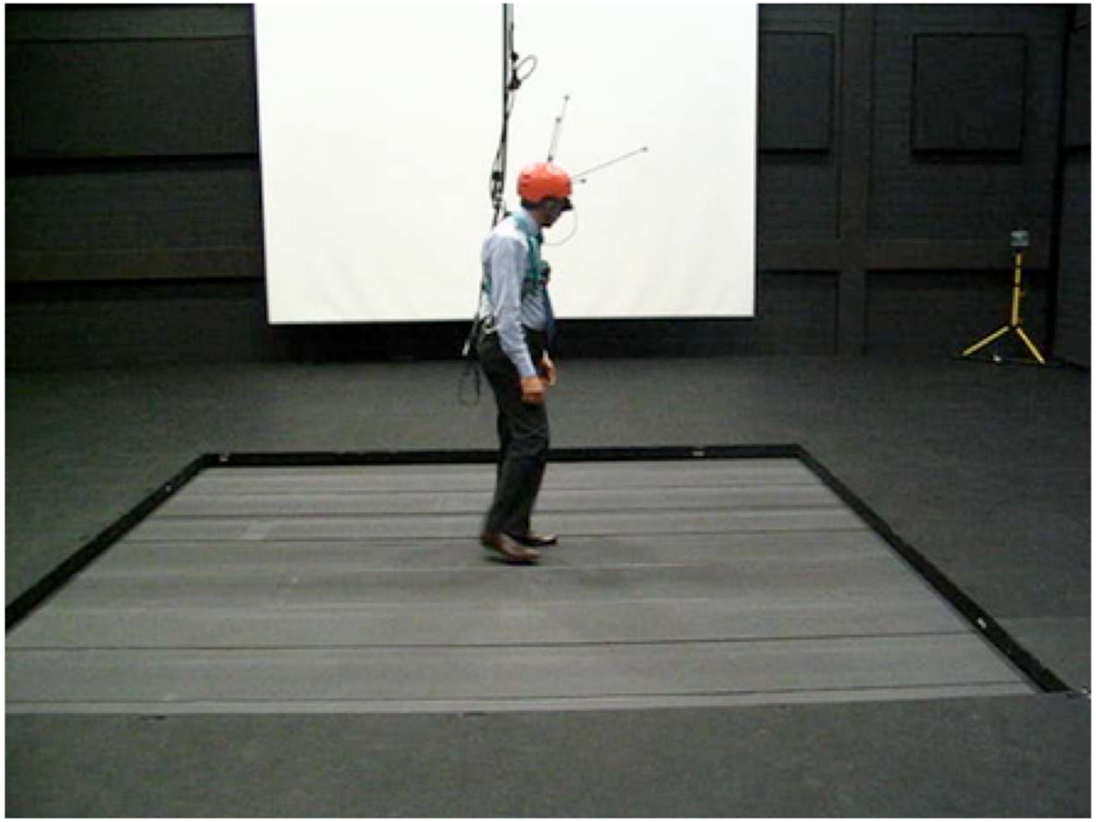
CyberWalk final workshop

April 2008

video

since then, tested with 100+ people @ Cyberneum, MPI Tübingen

Need for further improvements ...

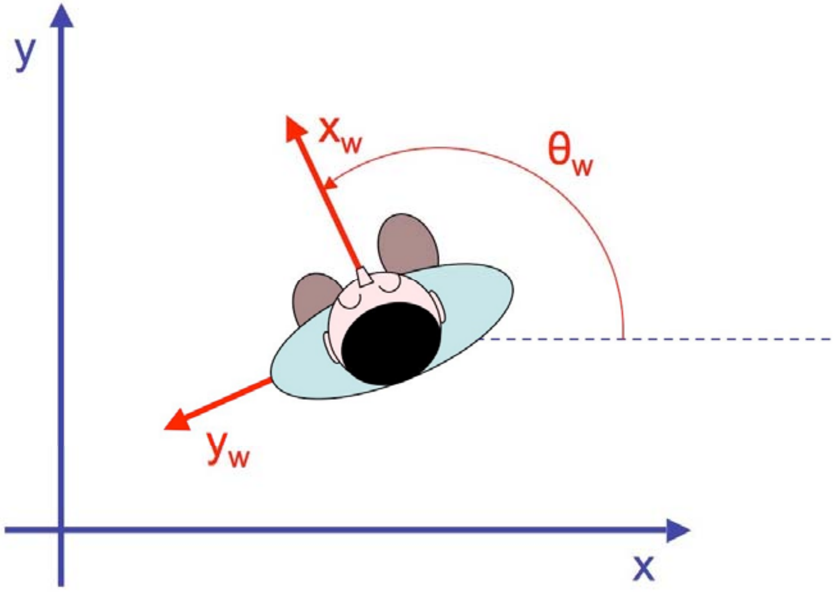


video

Selective control gains

based on walker orientation

- basic control design takes "equal" gains in x, y
  - axes are mechanically decoupled (double 1D design)
- humans are more sensitive to lateral (y_w) acceleration
- use then gains that are "larger" in x_w and smaller in y_w
- needs body (not head) orientation
- overhead camera(s) may be used, in addition/alternative to Vicon



$$a_c = -\hat{a}_w - k_v \hat{v} + k_p (x_{ref} - x)$$

(same for y direction)

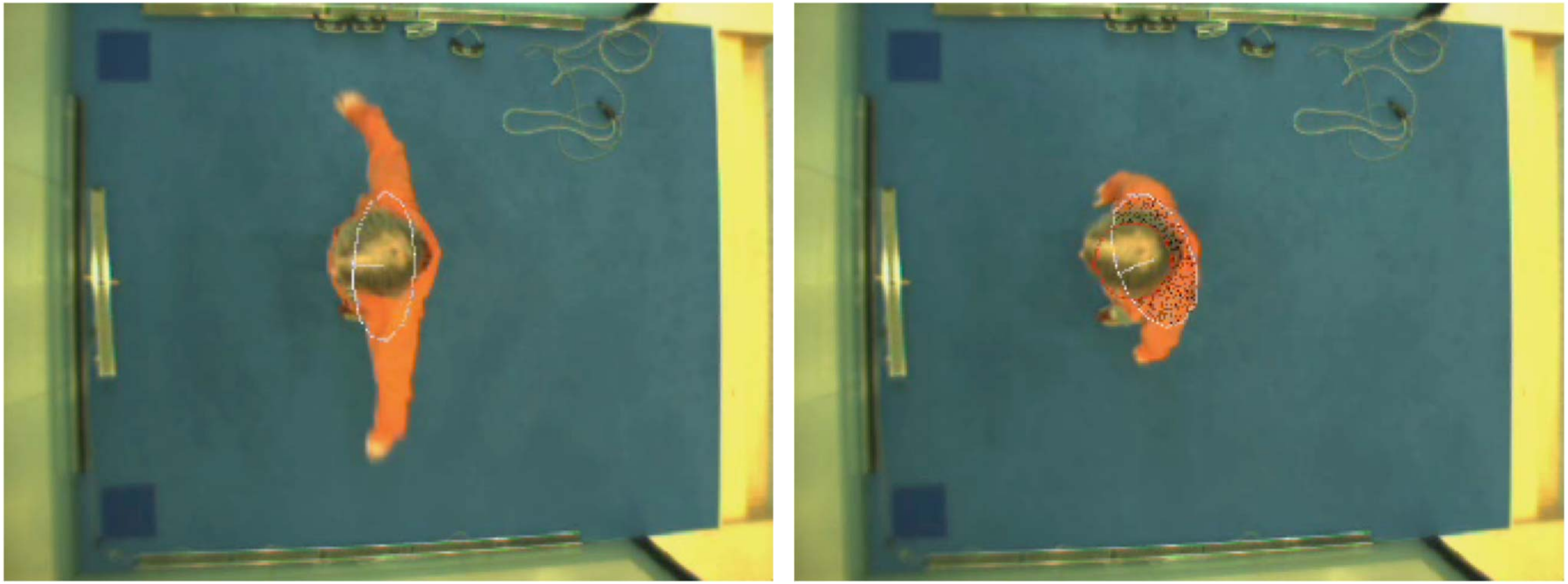
$$K_p(\theta_w) = R(\theta_w) K_{p_w} R^T(\theta_w)$$

$$K_{p_w} = \mathrm{diag}\{k_{p_{x_w}}, k_{p_{y_w}}\}$$

$$R(\theta_w) = \begin{bmatrix} \cos\theta_w & -\sin\theta_w \\ \sin\theta_w & \cos\theta_w \end{bmatrix}$$

Full-body visual tracking

from a single overhead camera



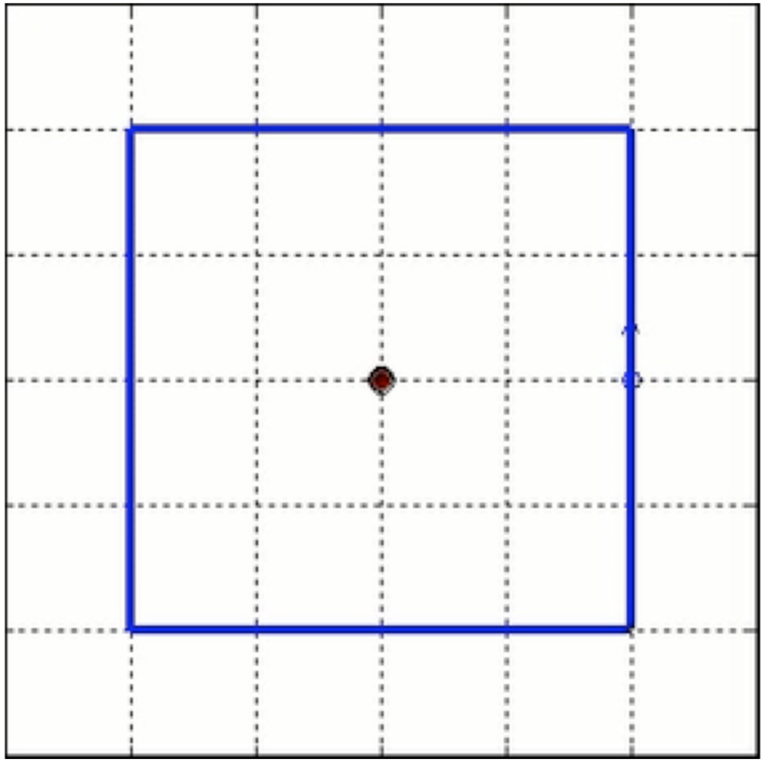
ellipsoid (shoulders) model only

ellipsoid plus circle (head) model

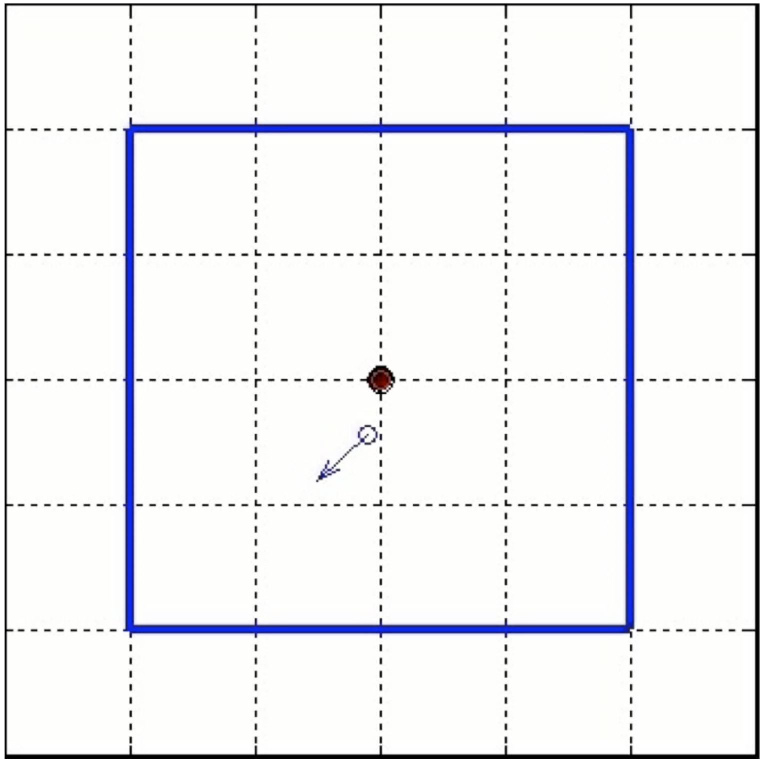
on-line localization of walker position & orientation
using a color-based particle filter method

Simulation

selective control gains strategy



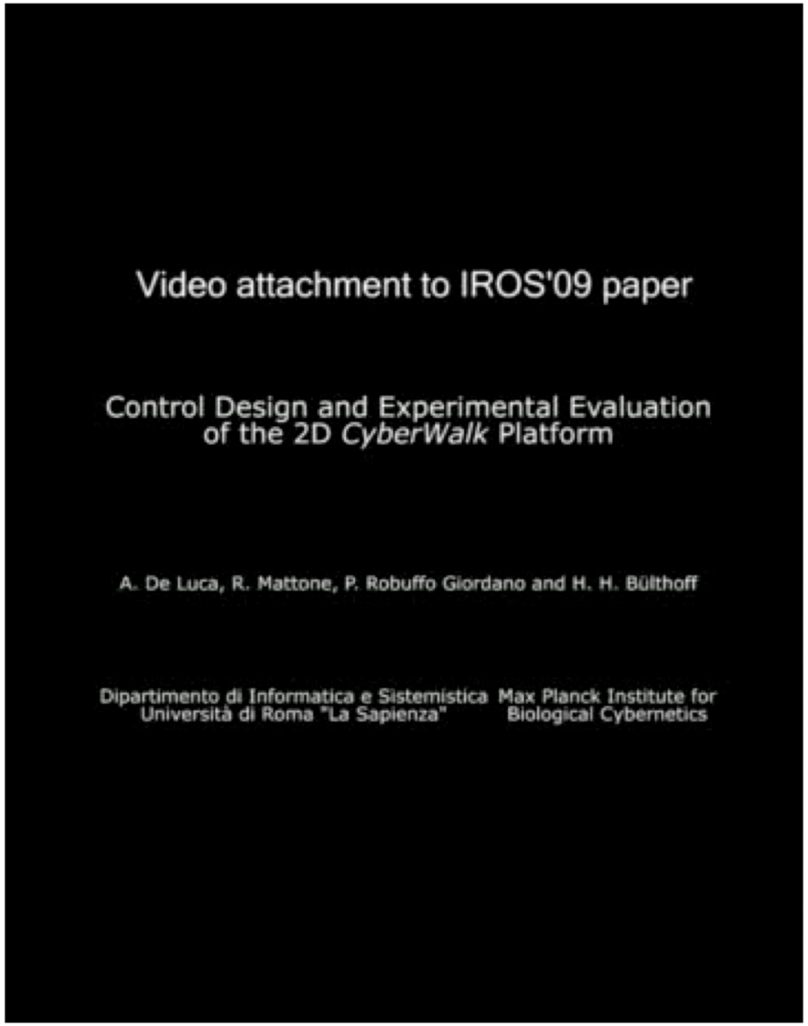
square (ccw) path, starting at the border



generic (random) walk

pointing arrow is the pose (position and orientation) of the walker in motion,
empty brown circle is the reference position, **full black circle** is the platform center

Latest experiments



Video attachment to IROS'09 paper

Control Design and Experimental Evaluation
of the 2D *CyberWalk* Platform

A. De Luca, R. Mattone, P. Robuffo Giordano and H. H. Bülthoff

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Università di Roma "La Sapienza"

Max Planck Institute for
Biological Cybernetics

video

see also
http://www.youtube.com/
watch?v=Af0Skxi4ftw

featured also in http://spectrum.ieee.org/automaton/robotics/robotics-software/
cyberwalk-giant-omnidirectional-treadmill-to-explore-virtual-worlds

Conclusions

- lessons learned
  - high data rate (30 Hz – 50 Hz) allows very fast control reaction, which may not meet perceptual/comfort constraints
  - too slow rate (<10 Hz) leads to jerky and oscillatory control
  - slow reaction when user is still, fast reaction when is moving
  - avoid discontinuities in acceleration/jerk
  - adjust thresholds and gains according to the "system state"
    - magnitude of walker intentional velocity
    - walker position w.r.t. the “zero” reference
    - different set of gains according to walker status (still, walking, running) and “experience”

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Swiss Federal Institute of Technology Zurich

BIWI
Computer Vision

SAPIENZA
UNIVERSITÀ DI ROMA
DIPARTIMENTO DI INFORMATICA
E SISTEMISTICA ANTONIO RUBERTI

- CyberWalk consortium
    - EU STREP FP6-511092 project (2005-2008)
    - Max Planck Institute for Bio-Cybernetics
        - perceptual analysis and integration
    - Technical University of Münich
        - mechanical design and construction
    - Eidgenossische Technische Hochschule Zürich
        - visual tracking and VR visualization
    - Sapienza Università di Roma
        - motion control design and implementation

www.cyberwalk-project.org

Bibliography

2D omnidirectional platform

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Ball-array CyberCarpet

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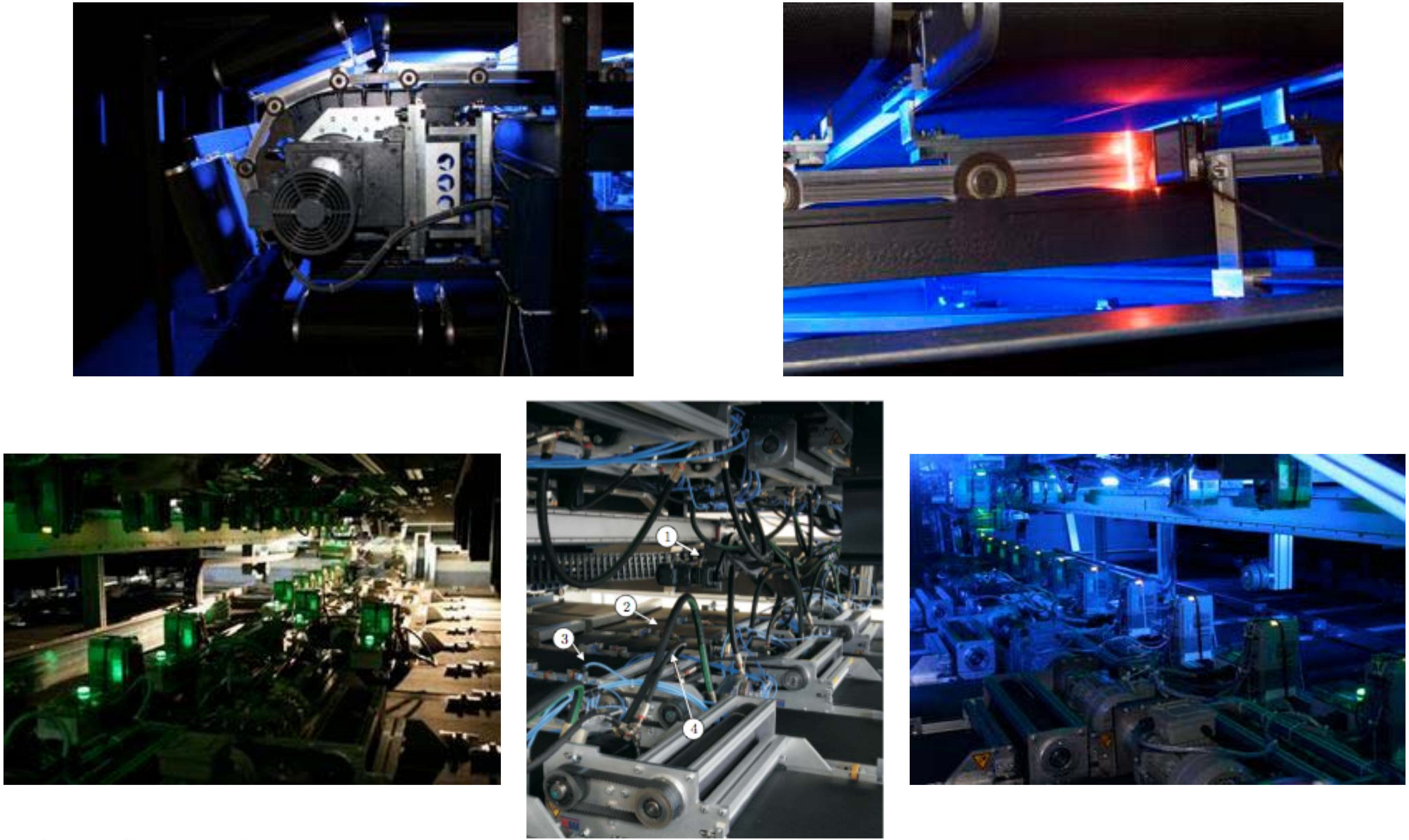
Videos/papers: http://www.dis.uniroma1.it/labrob/research/CW.html

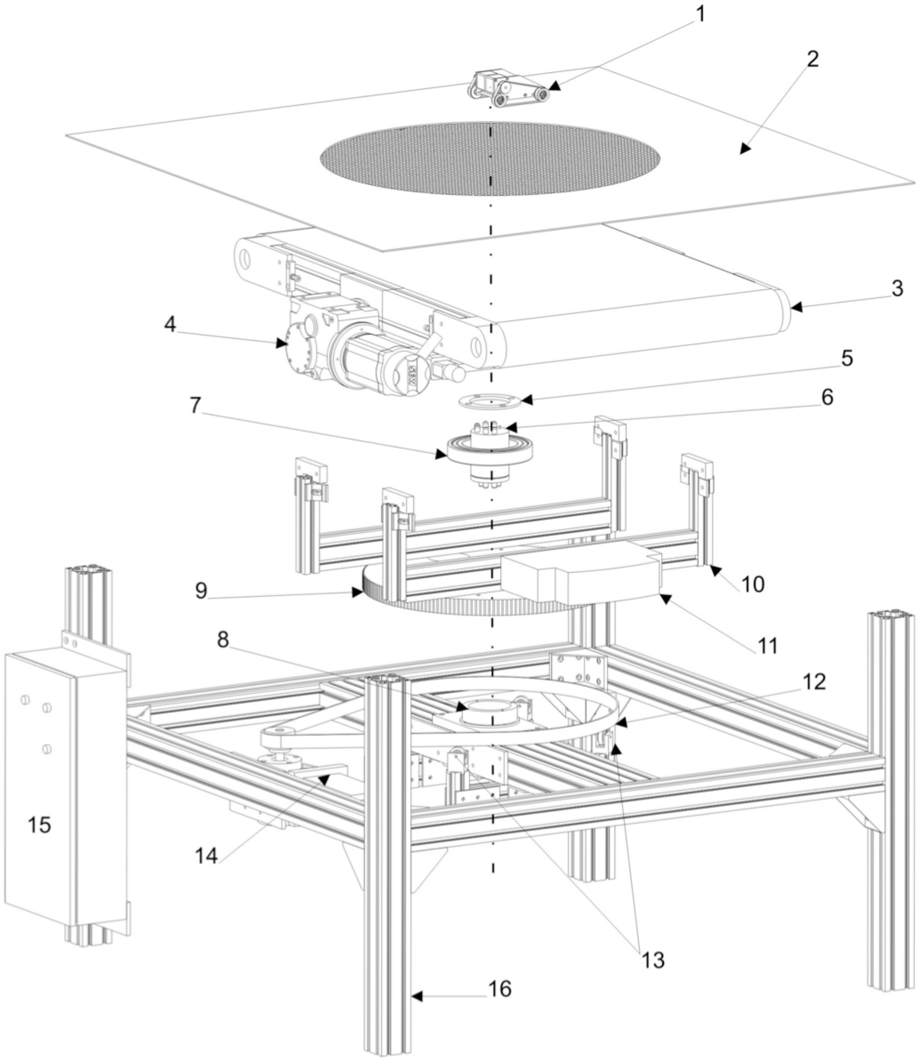
2D omnidirectional platform

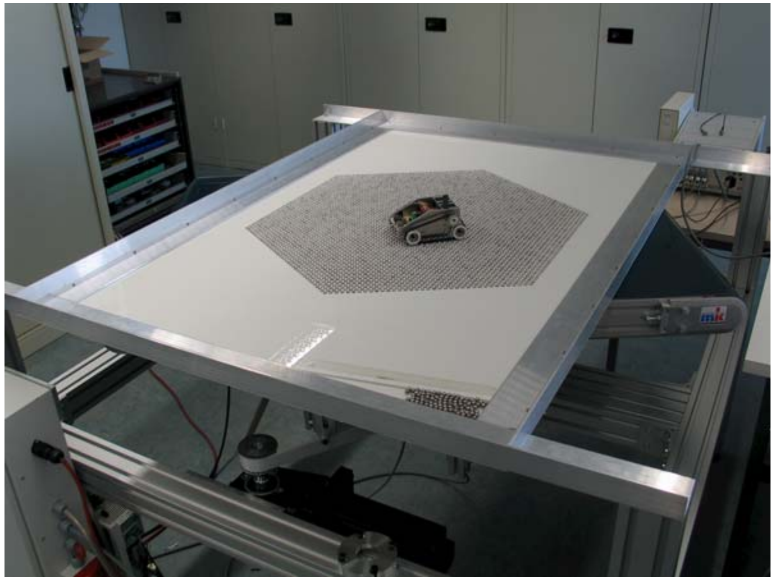
electric/hydraulic actuation

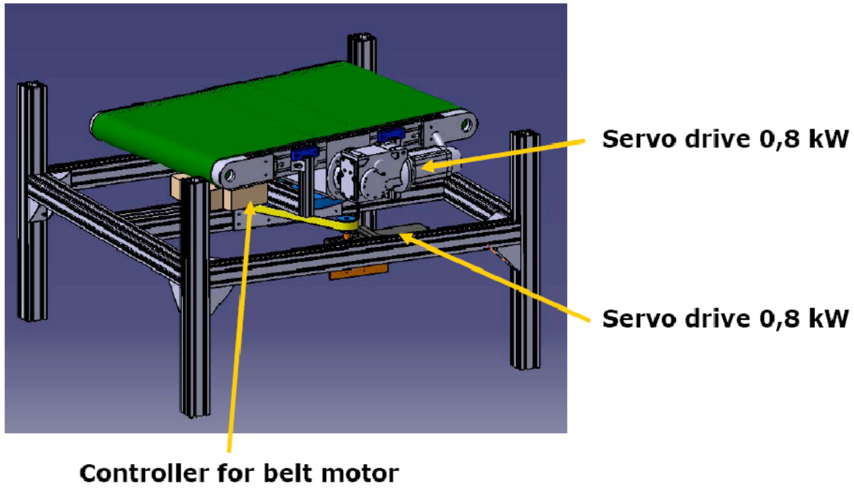


CyberCarpet ball-bearing platform

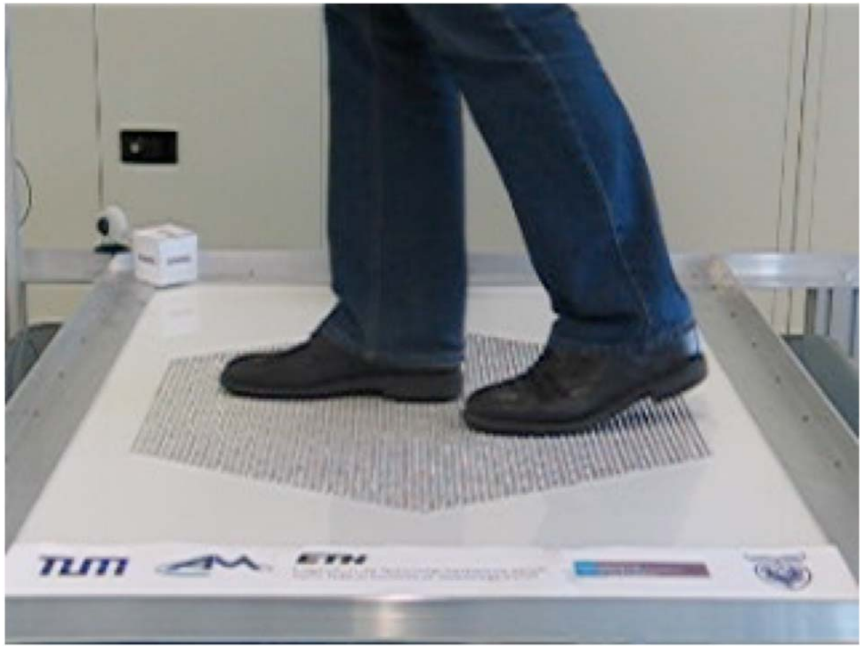
electro-mechanical assembly



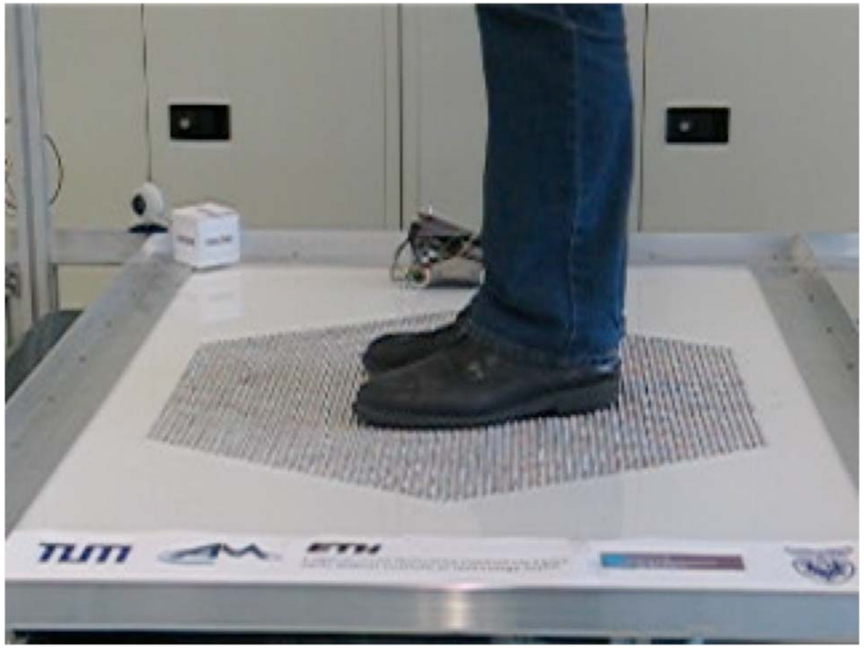




Human walking tests



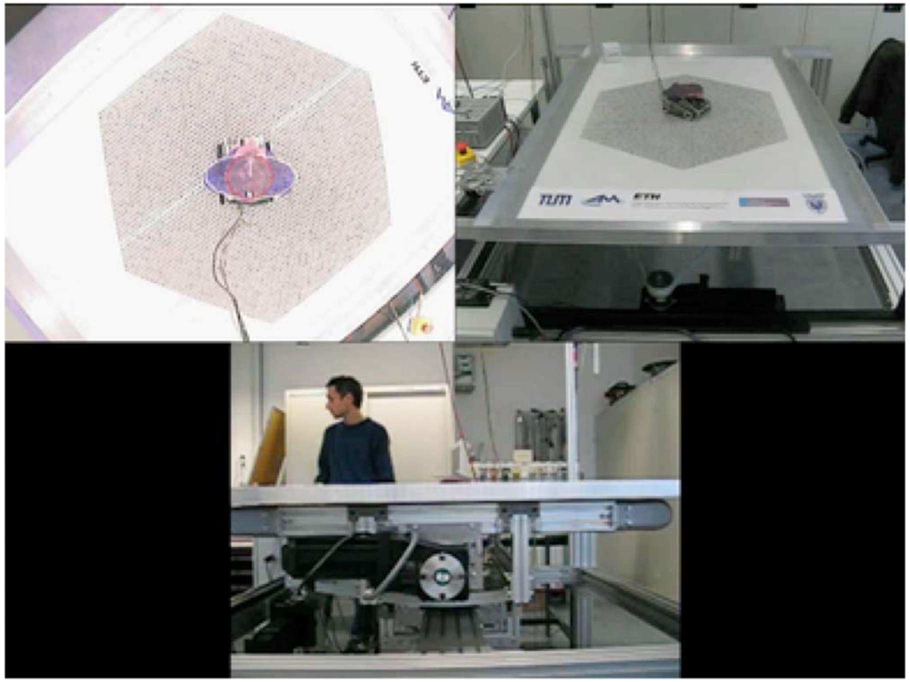
slow speed



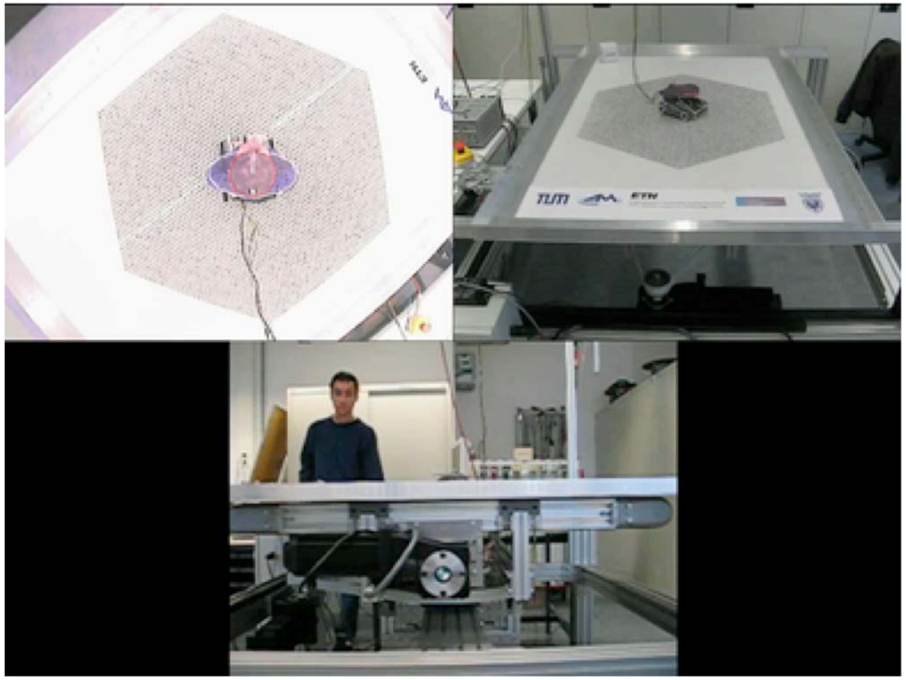
increasing speed
from zero to max (1.4 m/s)

Moving at constant velocity

using a mobile robot with human mock-up



- without feedforward

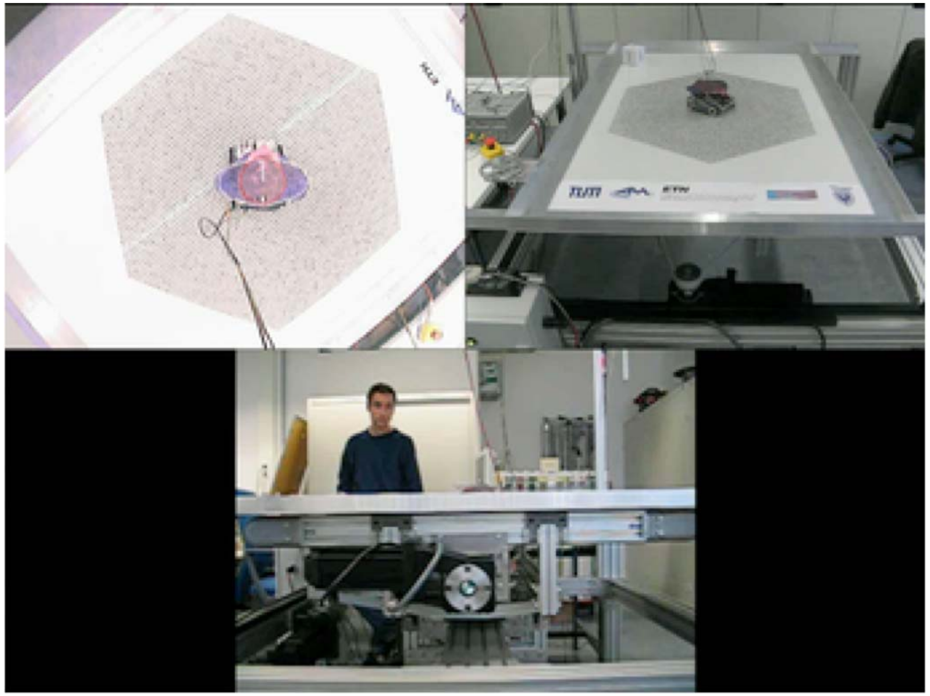


- with compensation of intentional velocity

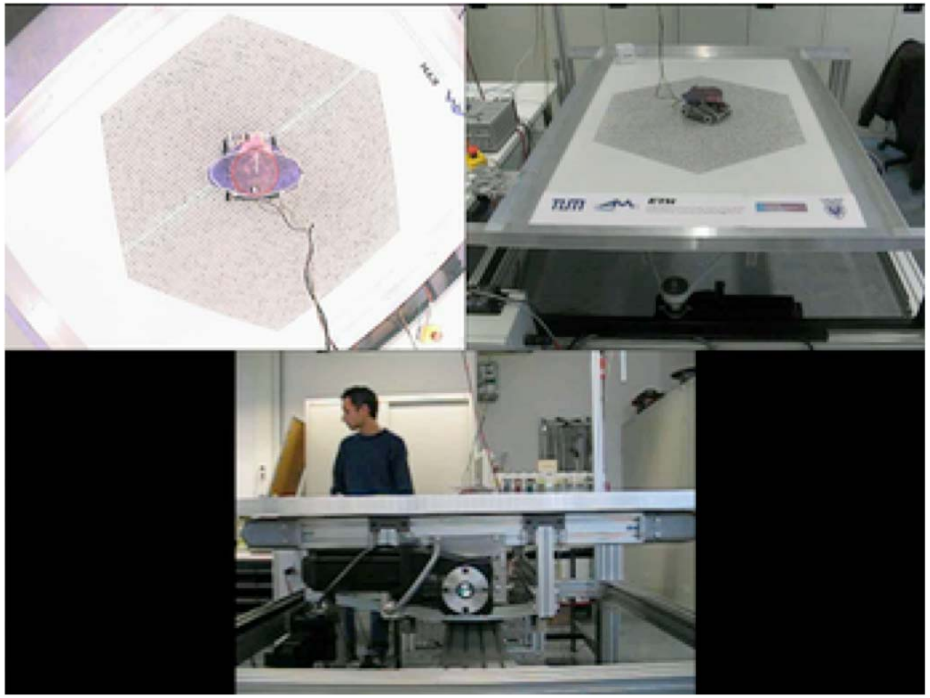
robot (unknown) velocity ~ 0.22 m/s

Traveling on circular and square paths

- with compensation of intentional velocity



circular path

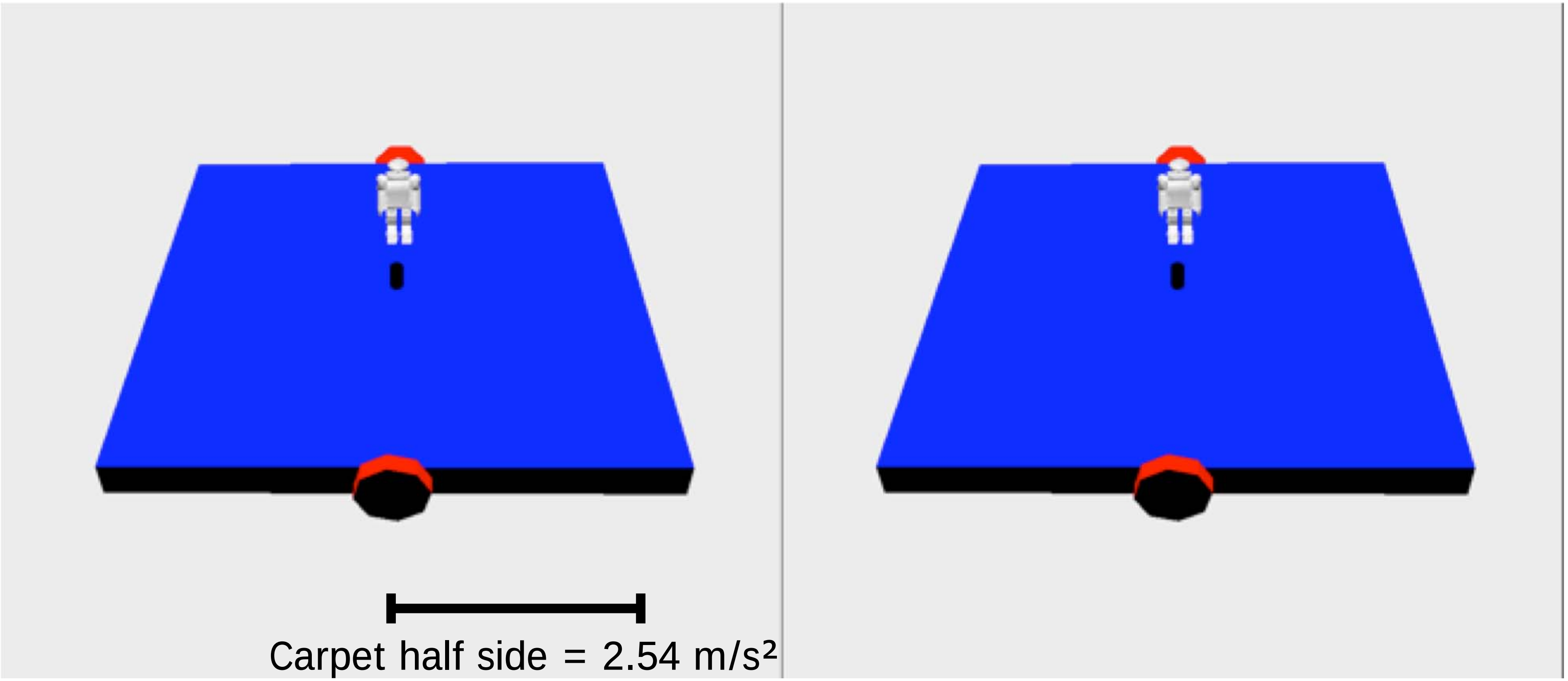


square path

Dynamic analysis

ball-bearing platform

- large size CyberCarpet under acceleration control
- walker: square path of side = 3 m, max velocity = 1.2 m/s (b-c-b acceleration)



inertial acceleration Coriolis acceleration centrifugal acceleration