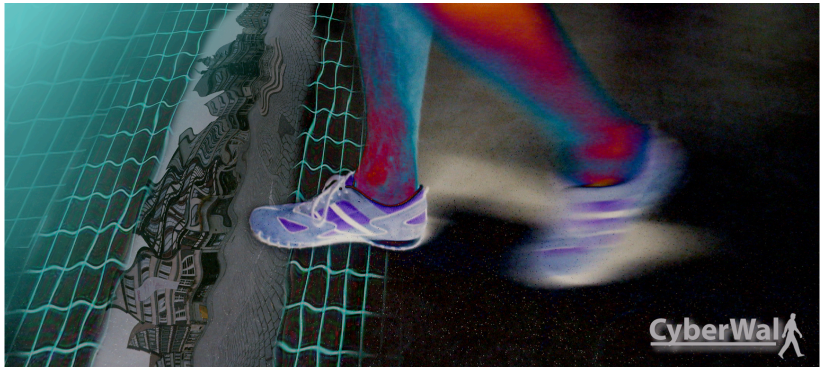
Elective in Robotics

Motion Control of the CyberWalk Platforms – Part II

EU STREP
FP6-511092 project
(2005-2008)



www.cyberwalk-project.org

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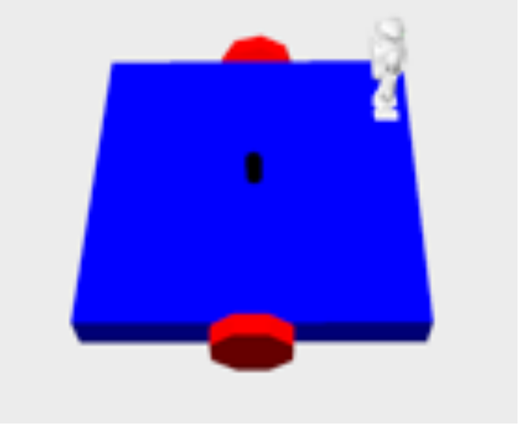
Sapienza
Università di Roma

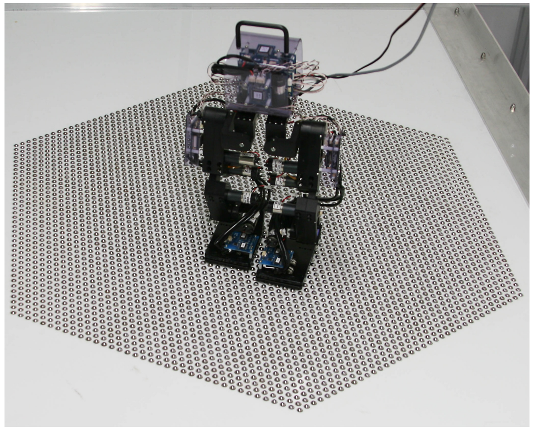
CyberWalk platforms

- ball-bearing
  - nonholonomic

simulation environment

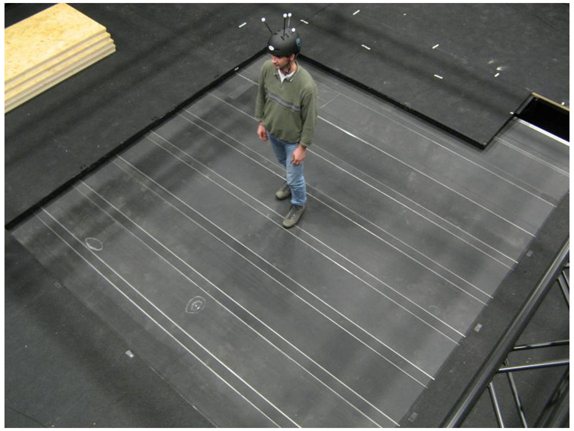


small-scale CyberCarpet



- belt(-array)
  - omnidirectional

1-D linear treadmill



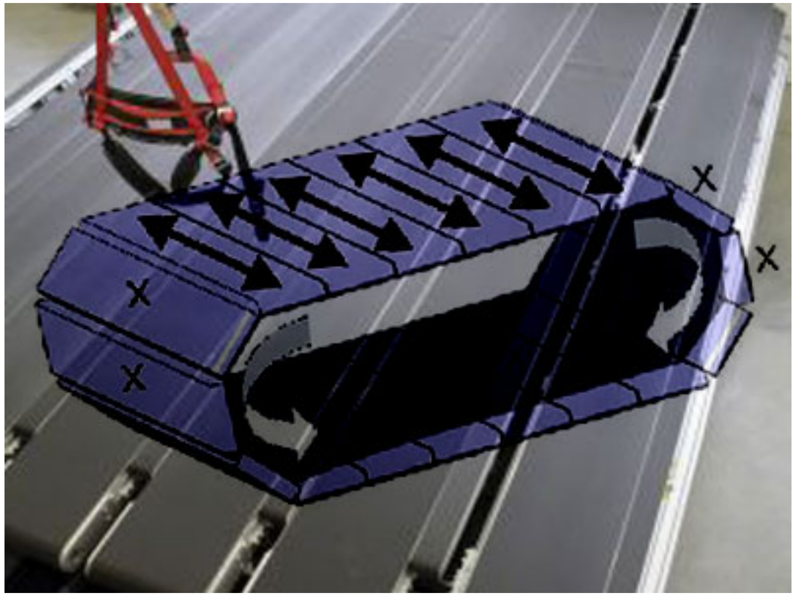
full-scale 2-D platform

Control specifications (again)

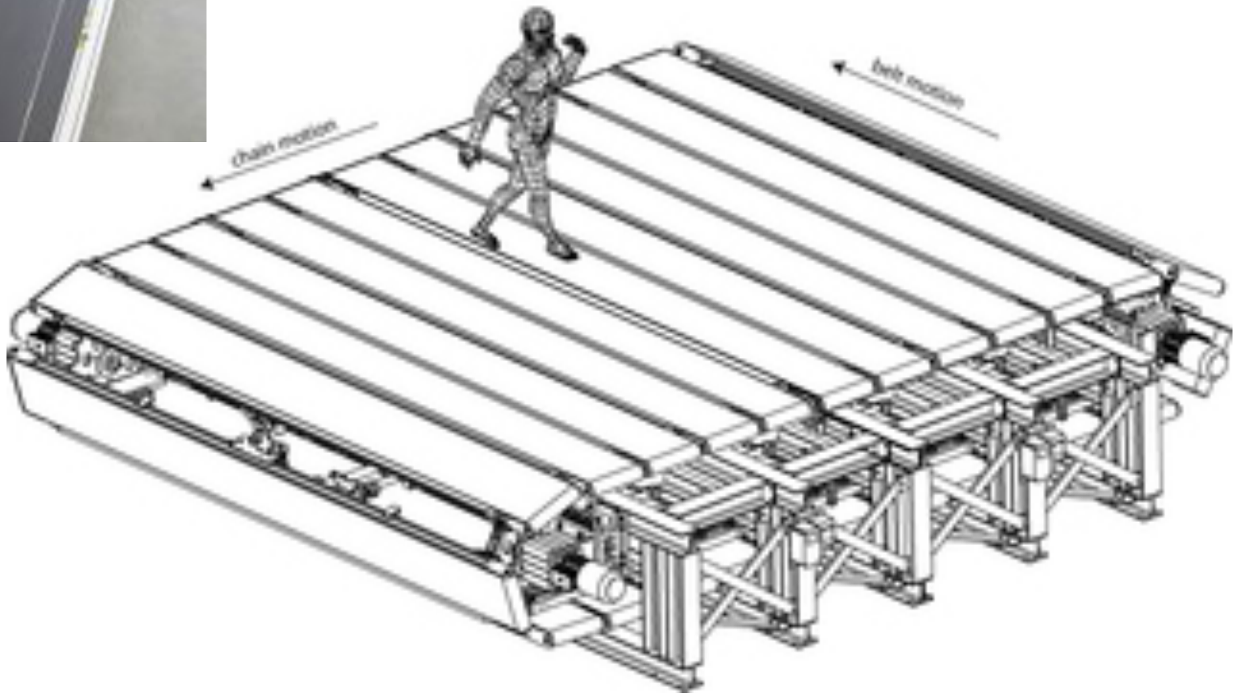
- keep the walker close to the platform center
    - taking into account platform dimensions
    - absolute orientation of walker is not relevant
- satisfy user's perceptual/comfort constraints
    - smoothly controlled motion, especially during start/stop transients
- only measurement of walker position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

Omnidirectional platform

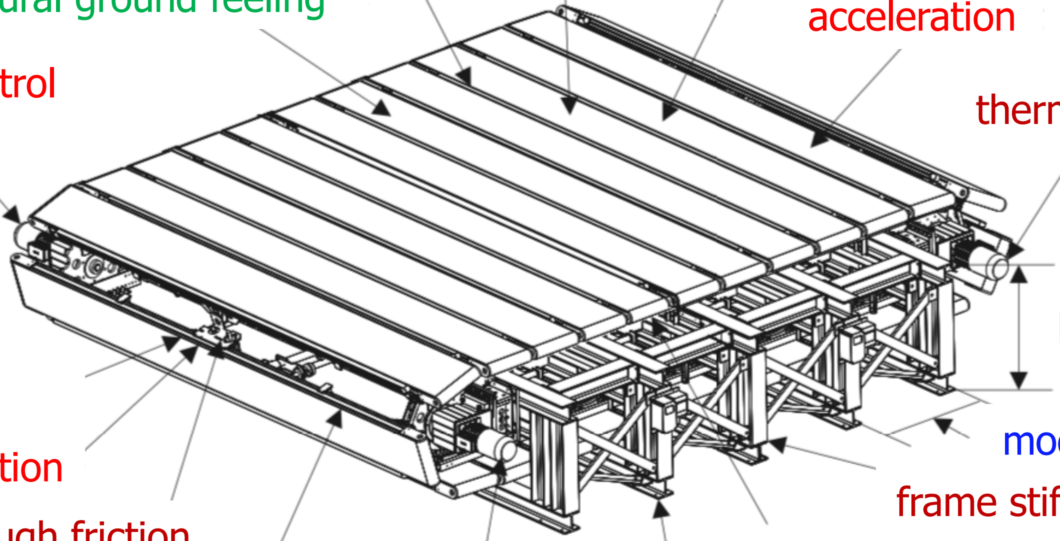
mechanical concept



25 treadmill belts
mounted on a chain



Omnidirectional platform
design specifications and characteristics



control &
communication
networking

cabling

endless rotation

energy consumption

gap-free

surface stiffness

size & weight

natural ground feeling

acceleration

motion control

thermic analysis

height

electrical
vs hydraulic
supply/actuation

modularity

frame stiffness

enough friction

position measurement

no "beats"

chain
actuation

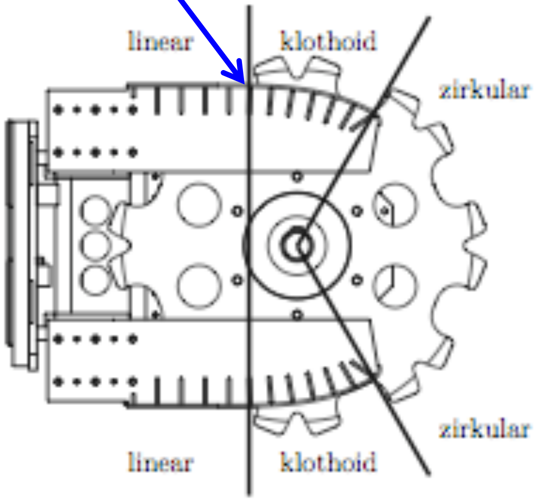
vibration decoupling

	a_{max}	v_{max}
individual treadmills (25)	> 1 m/s^2	1.4 m/s
principal chain	0.25 m/s^2	1.4 m/s

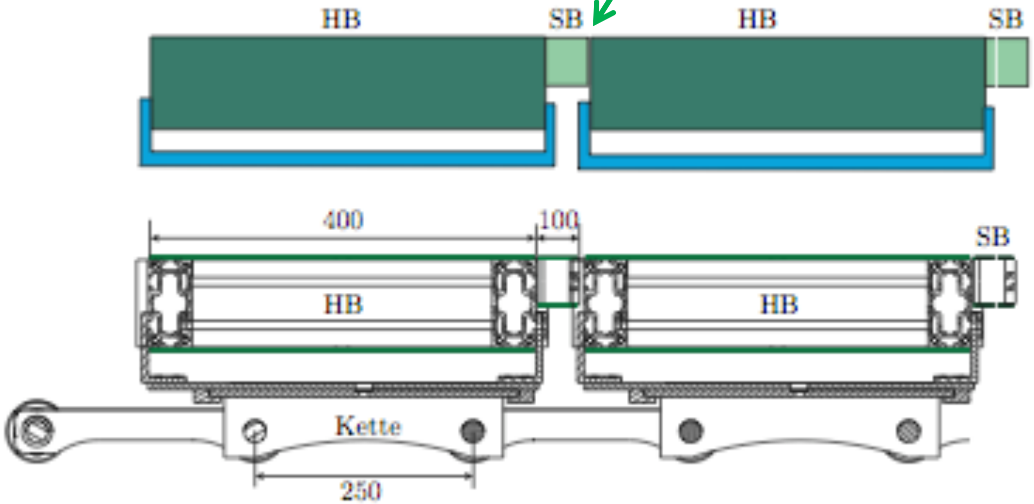
Omnidirectional platform

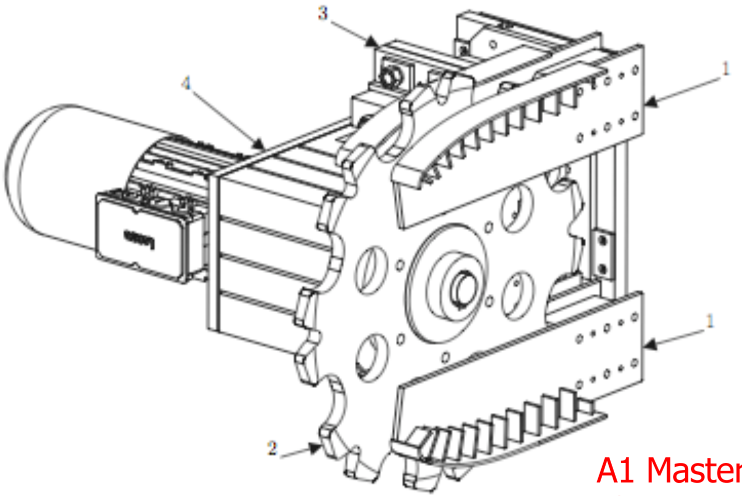
mechanical design and assembly of parts

continuous curvature profile (clothoid)



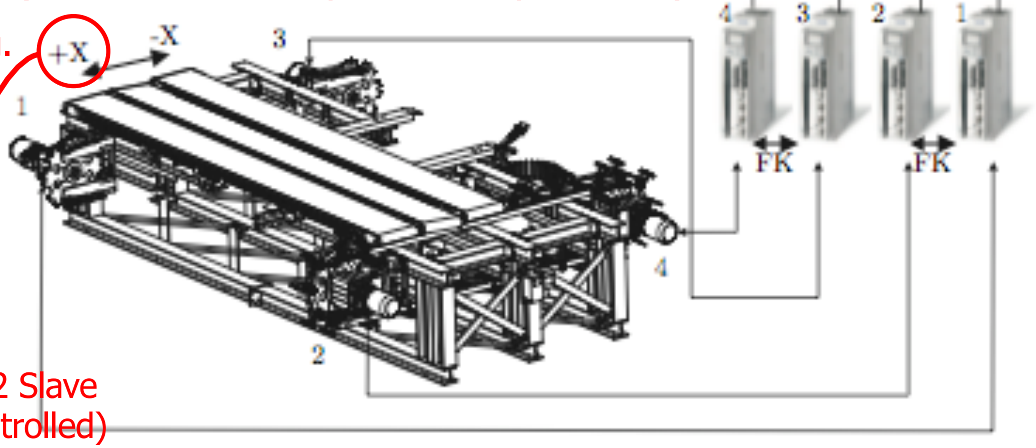
gap-free





4 electrical actuators for the two chains
(coordinated for synchronicity/tension)

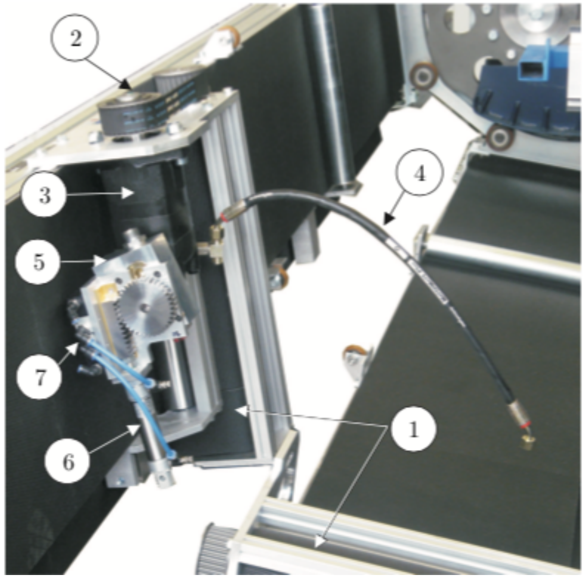
e.g.



A1 Master & A2 Slave
(frequency controlled)
A3 & A4 torque controlled

Omnidirectional platform

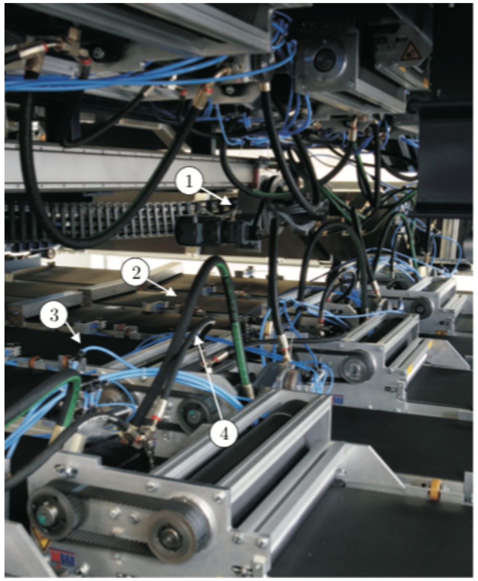
hydraulic vs. electric actuation of each treadmill



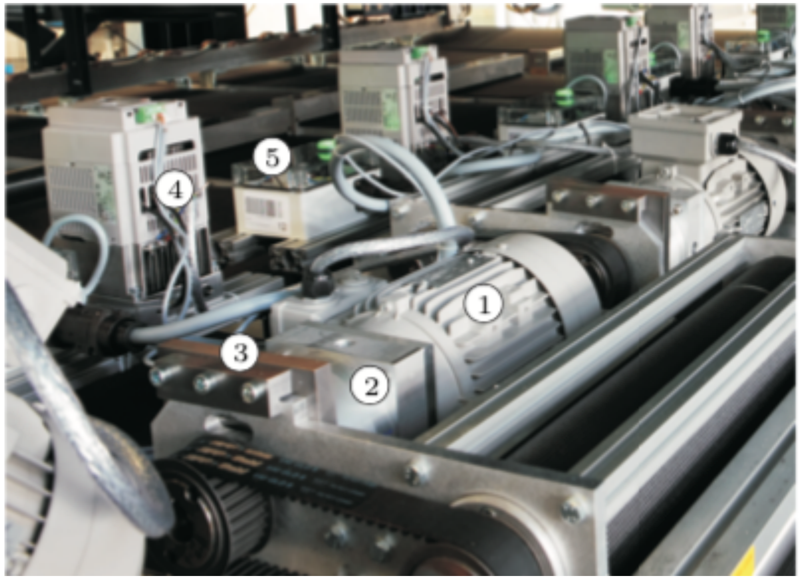
hydraulic actuation components

(1) transmission roller
(2) timing belt
(3) hydraulic actuator
(4) leakage pipe
(5) bypass valve
(6-7) pneumatic parts

operating pressure at ≈ 30 bar



hydraulic actuation
mounted for trial



AC electric motor: 90 Nm rated torque
1.5 kW, transmission ratio 1:10

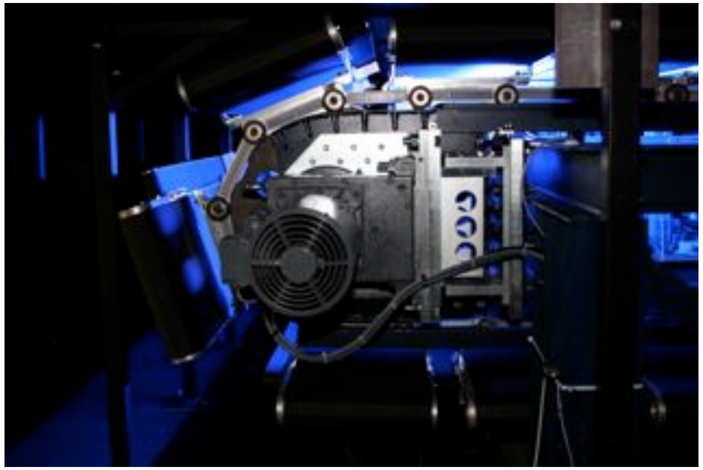
	hydraulic	electric
power density	+++	+
dynamic range	++	++
cost	–	+
safety of operation	– –	++
synchronism	++/– – –	+
behavior at start	+	++

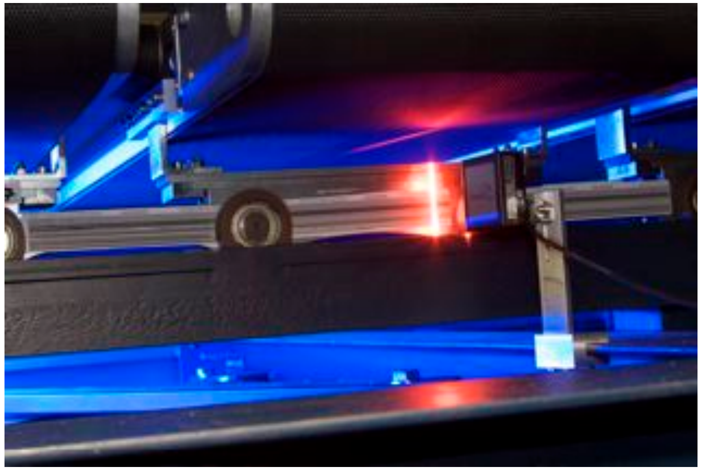
final choice

discarded due to excessive leakage

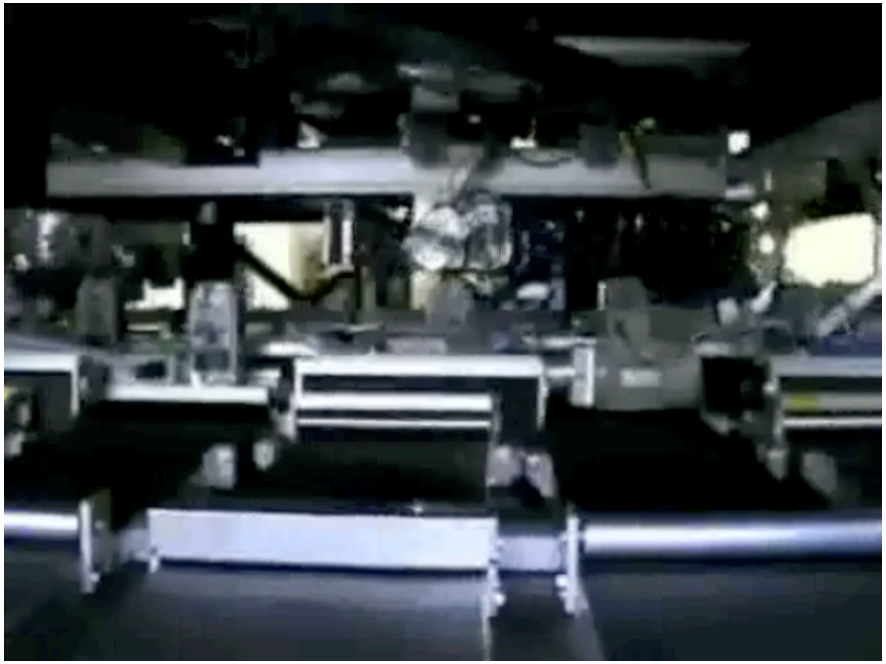
Omnidirectional platform

electric actuation of chain and barcode sensing





[four] 9.7kW AC asynchronous motors
with rated torque 1569Nm
(max platform speed 1.71 m/s)

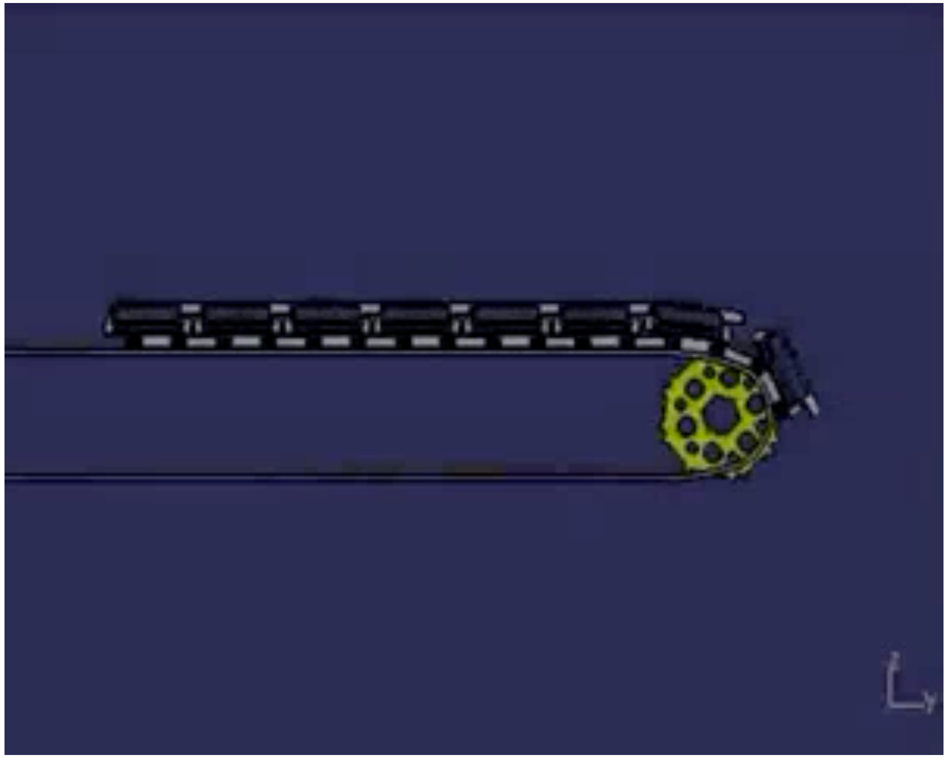


video

Omnidirectional platform

more technical insights..

video

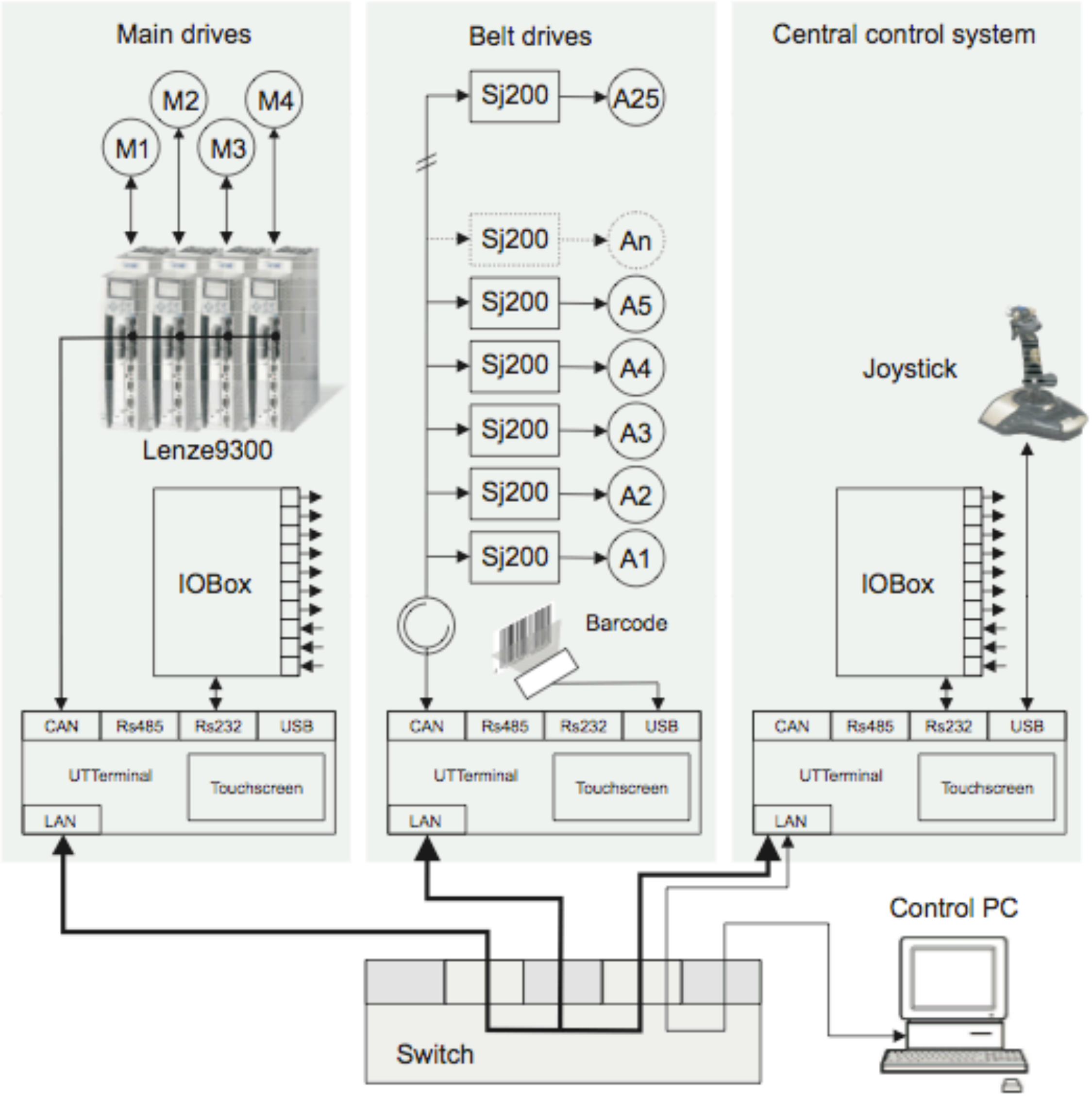


cycloid profile at the
motion reversal of the chain

video

from TU Munich to MPI Tübingen …
integrating various design stages

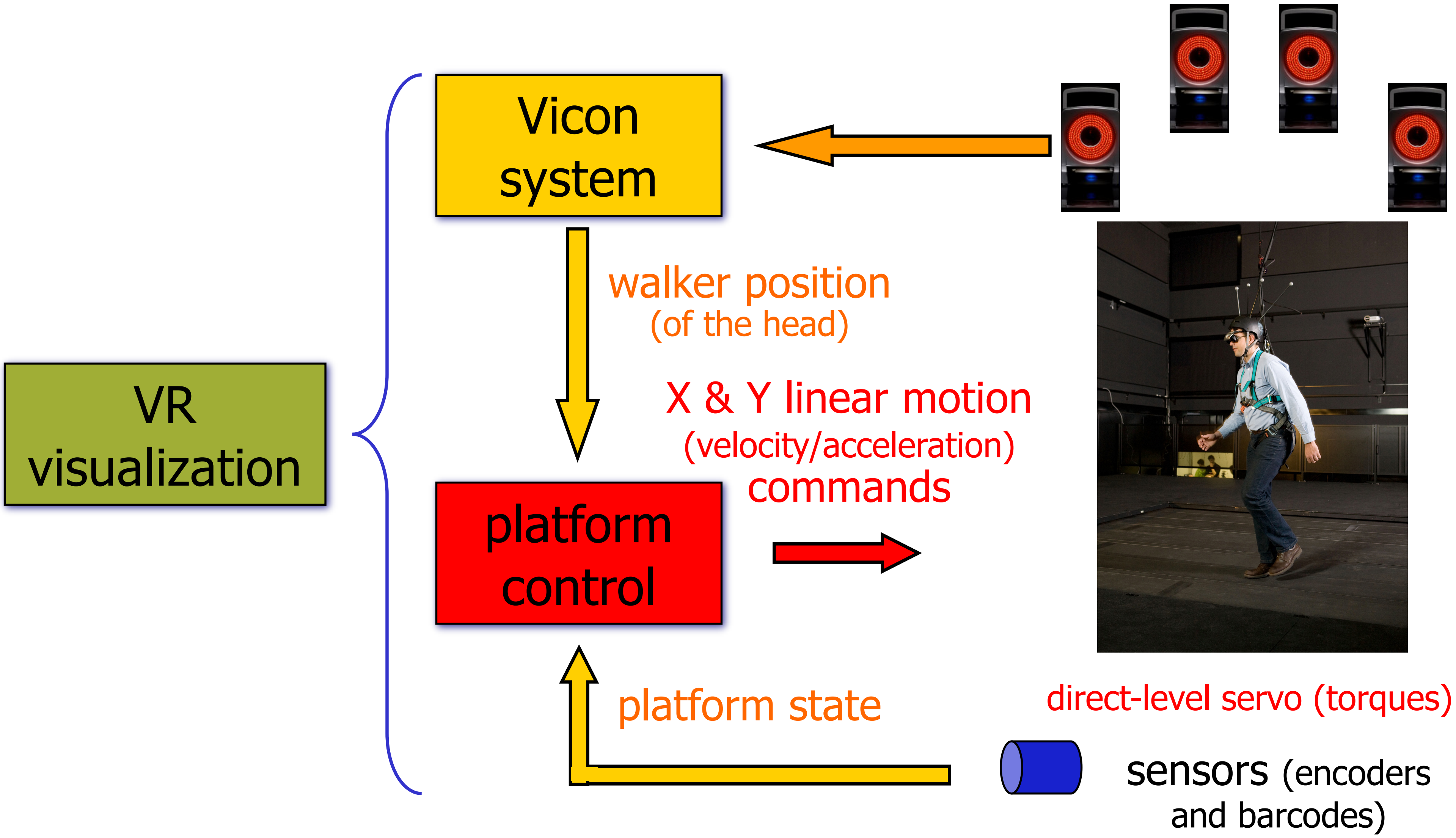
Control HW architecture



with HMI (Human-Machine Interface)

System architecture

omnidirectional platform



VR visualization

Vicon system

walker position (of the head)

platform control

X & Y linear motion (velocity/acceleration) commands

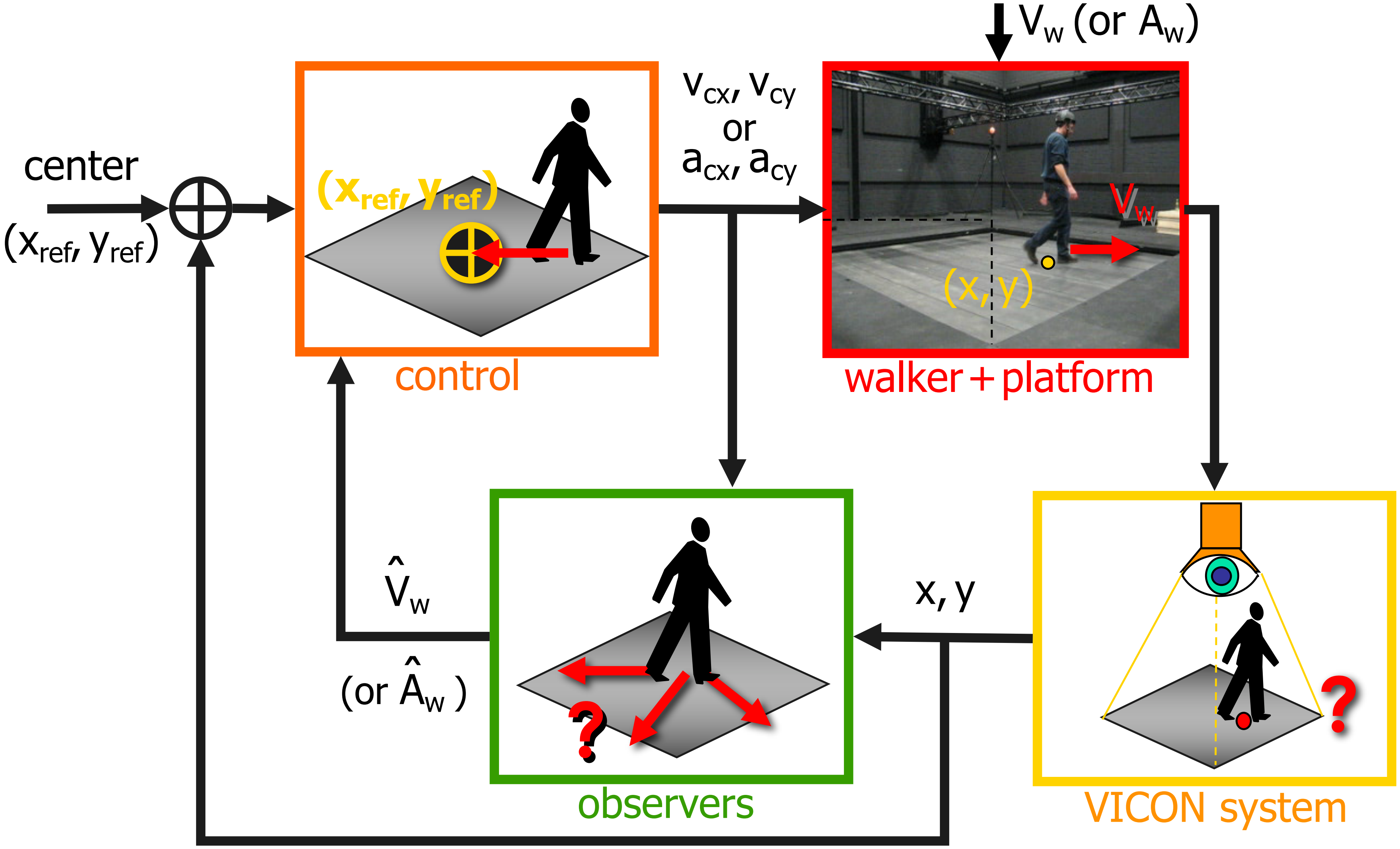
platform state

direct-level servo (torques)

sensors (encoders and barcodes)

Control principle

omnidirectional platform



Kinematic model

1-D/2-D omnidirectional platform

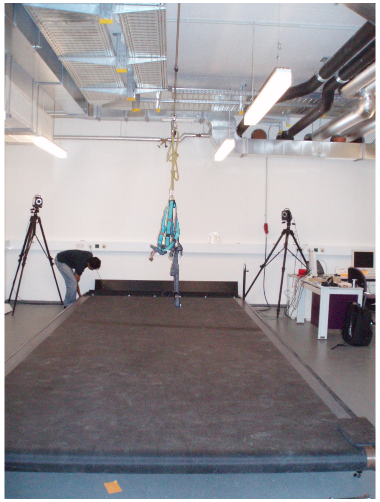
- second-order, linear, and decoupled model

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

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

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

- applies directly also to the 1-D linear treadmill...



Control design

1-D/2-D omnidirectional platform

- independent behavior in each direction ⟶ 1-D 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, exponential stable equilibrium at x_{ref}

- two separate observers of walker acceleration a_w and velocity v

$$\begin{cases} \dot{\xi}_1 &= \xi_2 + k_1(x - \xi_1) \\ \dot{\xi}_2 &= a_c + k_2(x - \xi_1) \\ \hat{a}_w &= k_2(x - \xi_1) \end{cases} \qquad \begin{cases} \dot{\xi}_3 &= k_3(x - \xi_3) \\ \hat{v} &= k_3(x - \xi_3) \end{cases}$$

provide (stable) low-pass filtered versions

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

- actual feedback law

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

Modified position reference
1-D/2-D omnidirectional platform

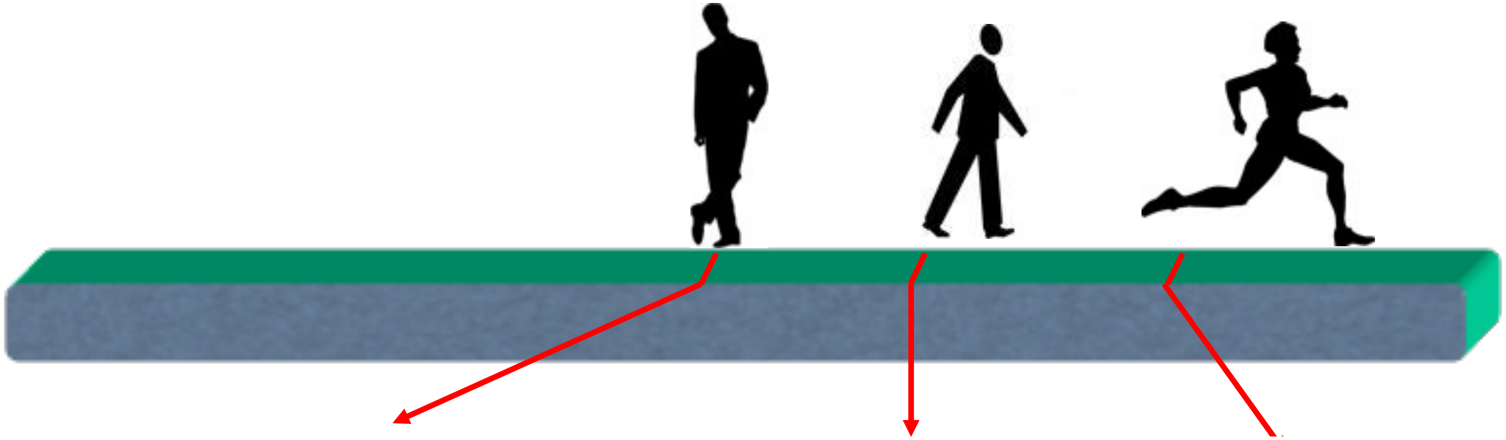
- a useful idea: modify x_{ref} according to the user own velocity

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

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 halts, more space available to stop the platform motion



$x_{ref,0}$ for standing

x_{ref} for walking

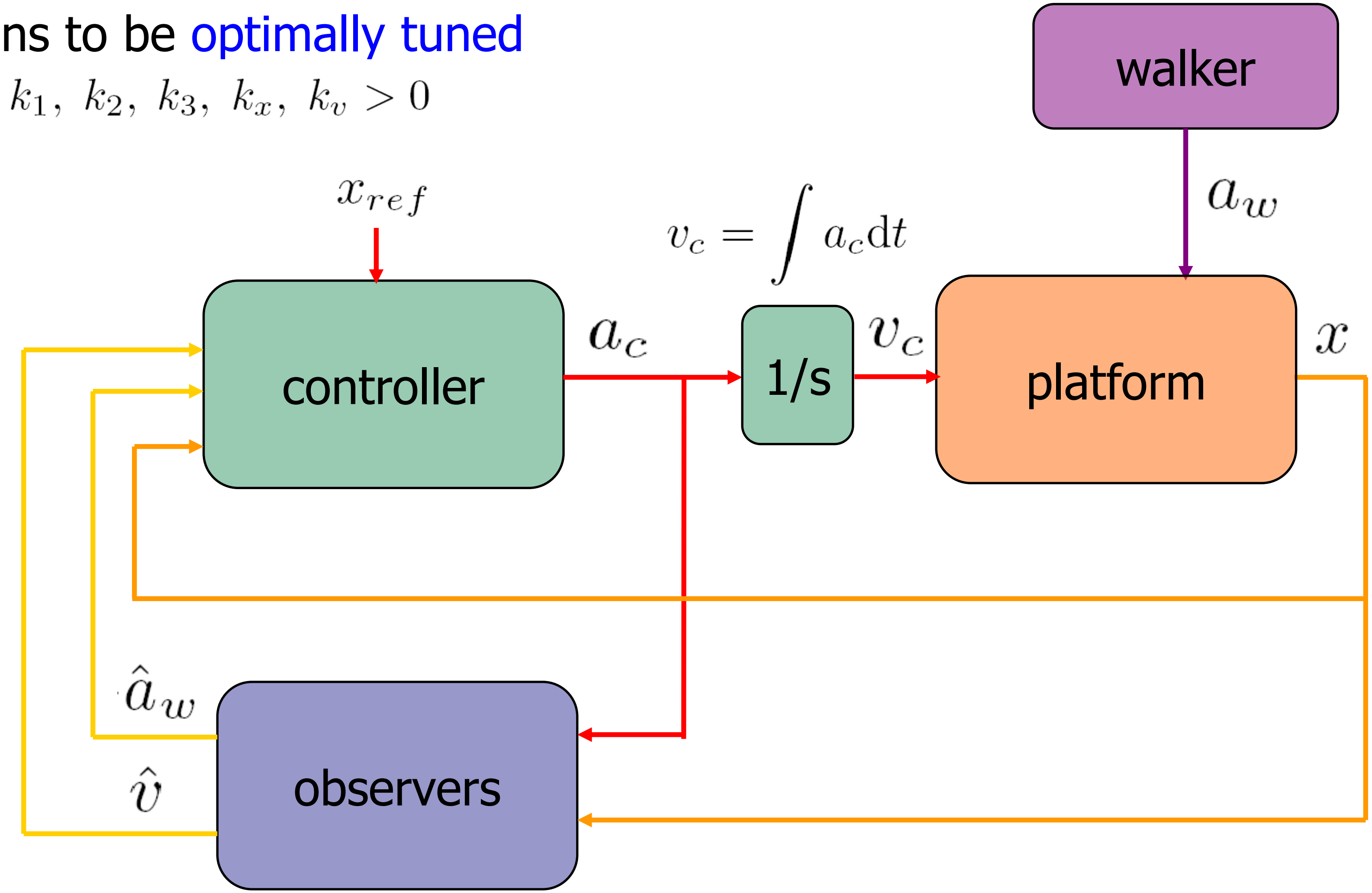
x_{ref} for running

Final control scheme

1-D/2-D omnidirectional platform

gains to be optimally tuned

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



$v_c = \int a_c \mathrm{d}t$

walker

controller

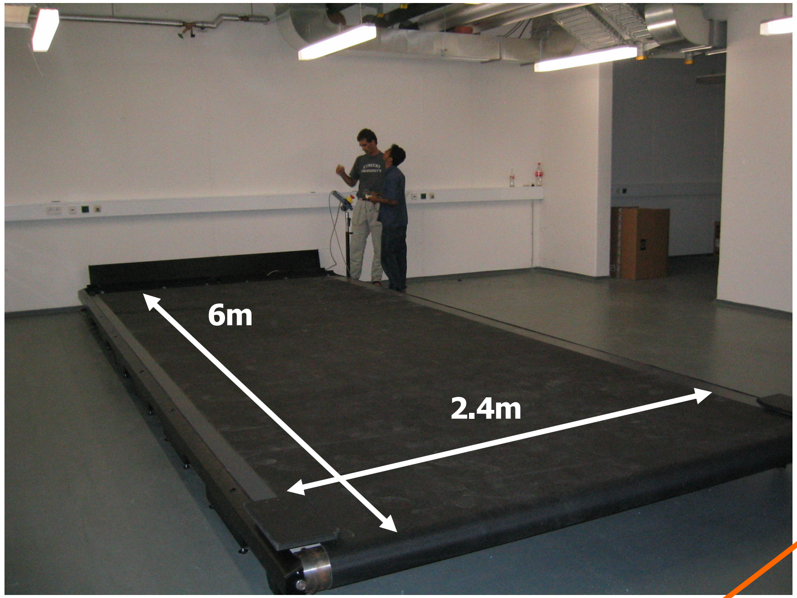
1/s

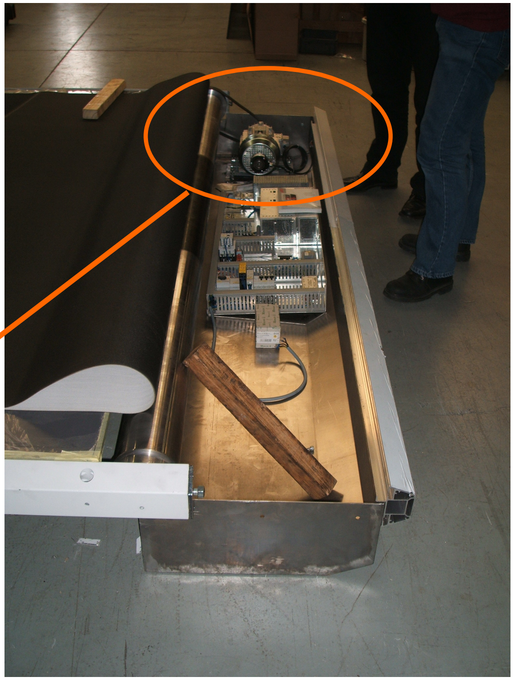
platform

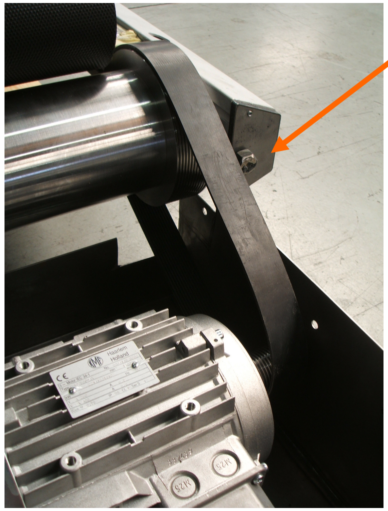
observers

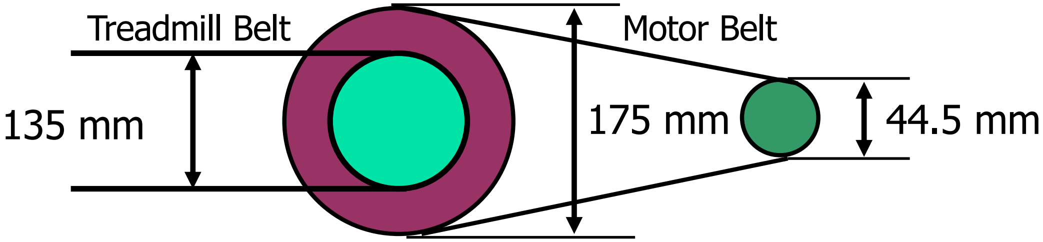
1-D linear treadmill

electrical actuation and transmission









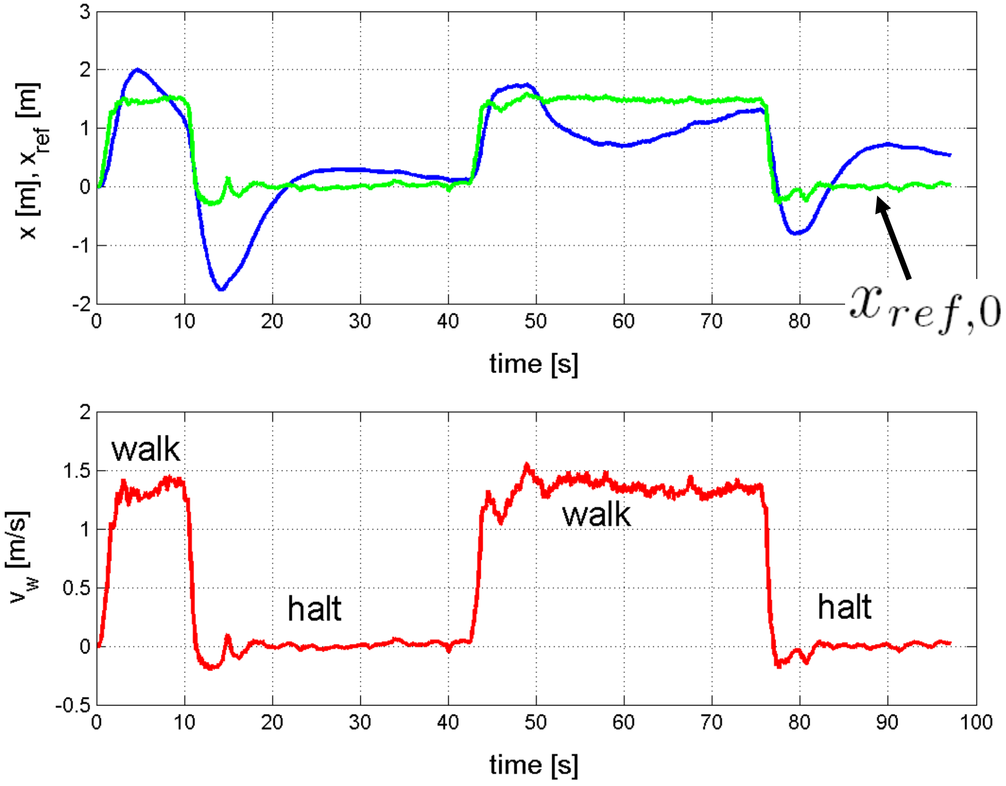
Experiments

1-D linear treadmill

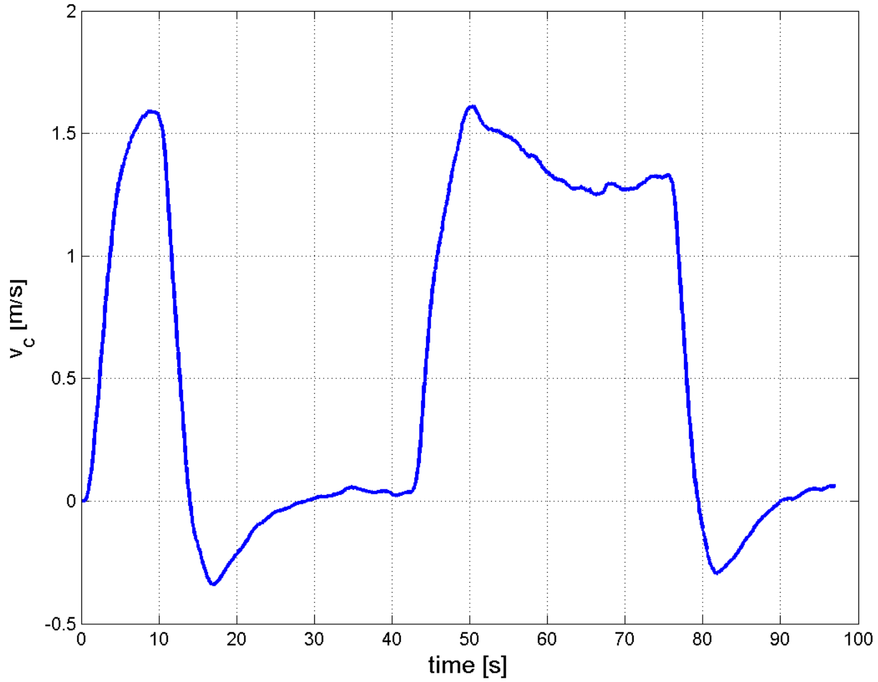
size: 6 m × 2.4 m

- 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

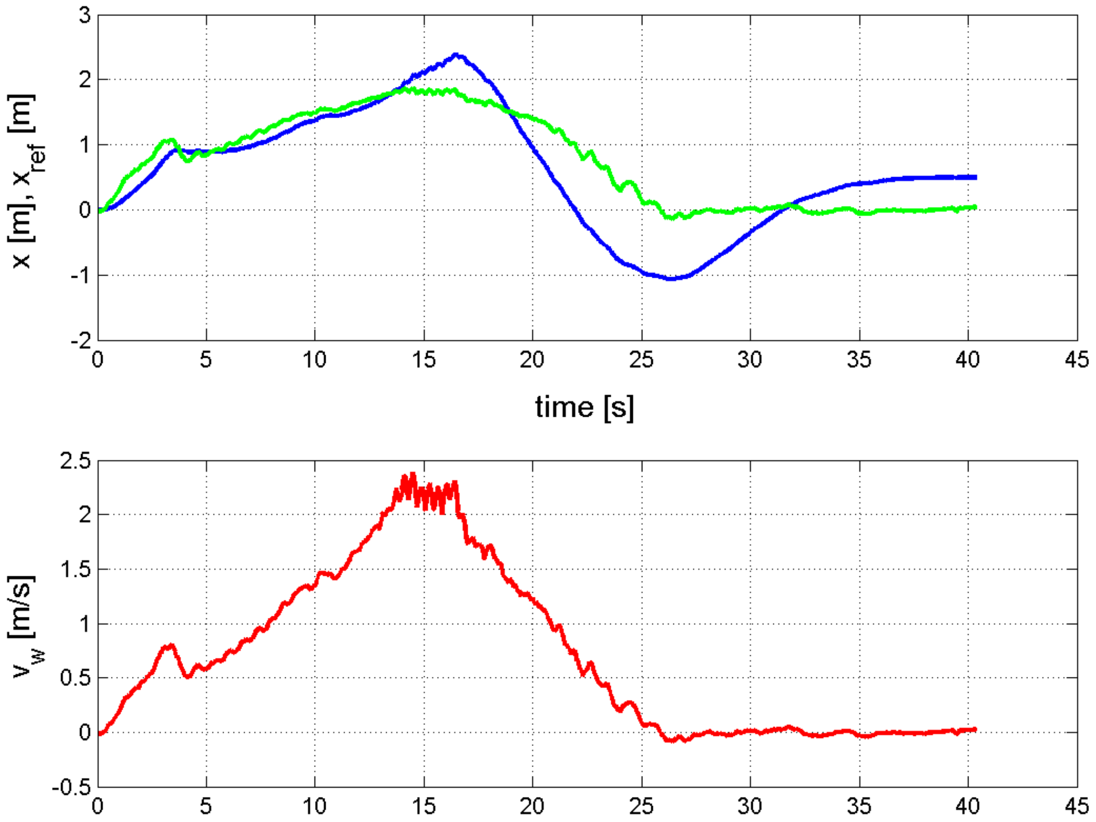


velocity command
sent to the carpet

no velocity/acceleration jumps

ends with horizontal tangent
(zero acceleration)

Accelerate/decelerate



walker position and
reference position

walker estimated
velocity
(**~ trapezoidal!**)

Random walk

1-D linear treadmill

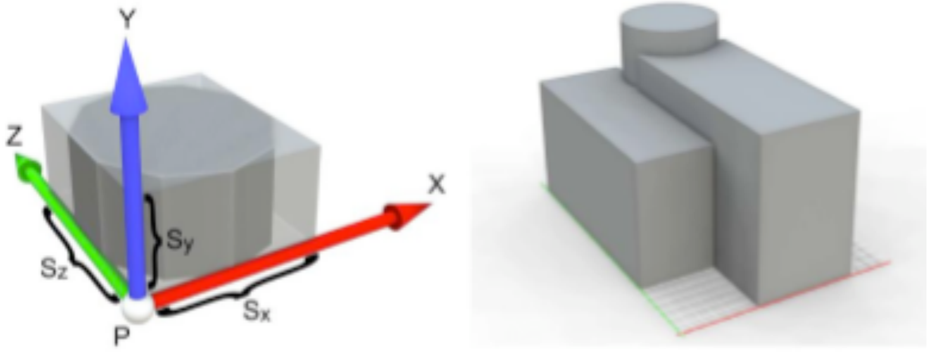
video

1-D circular treadmill

video

@ Max Planck Institute for Biological Cybernetics, Tübingen

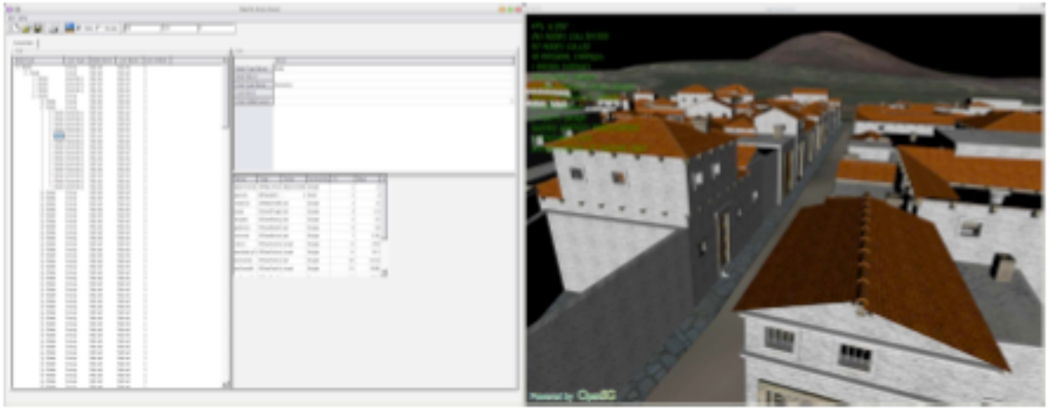
VR modeling by CityEngine



architectural procedural language


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

levels of detail in rendering

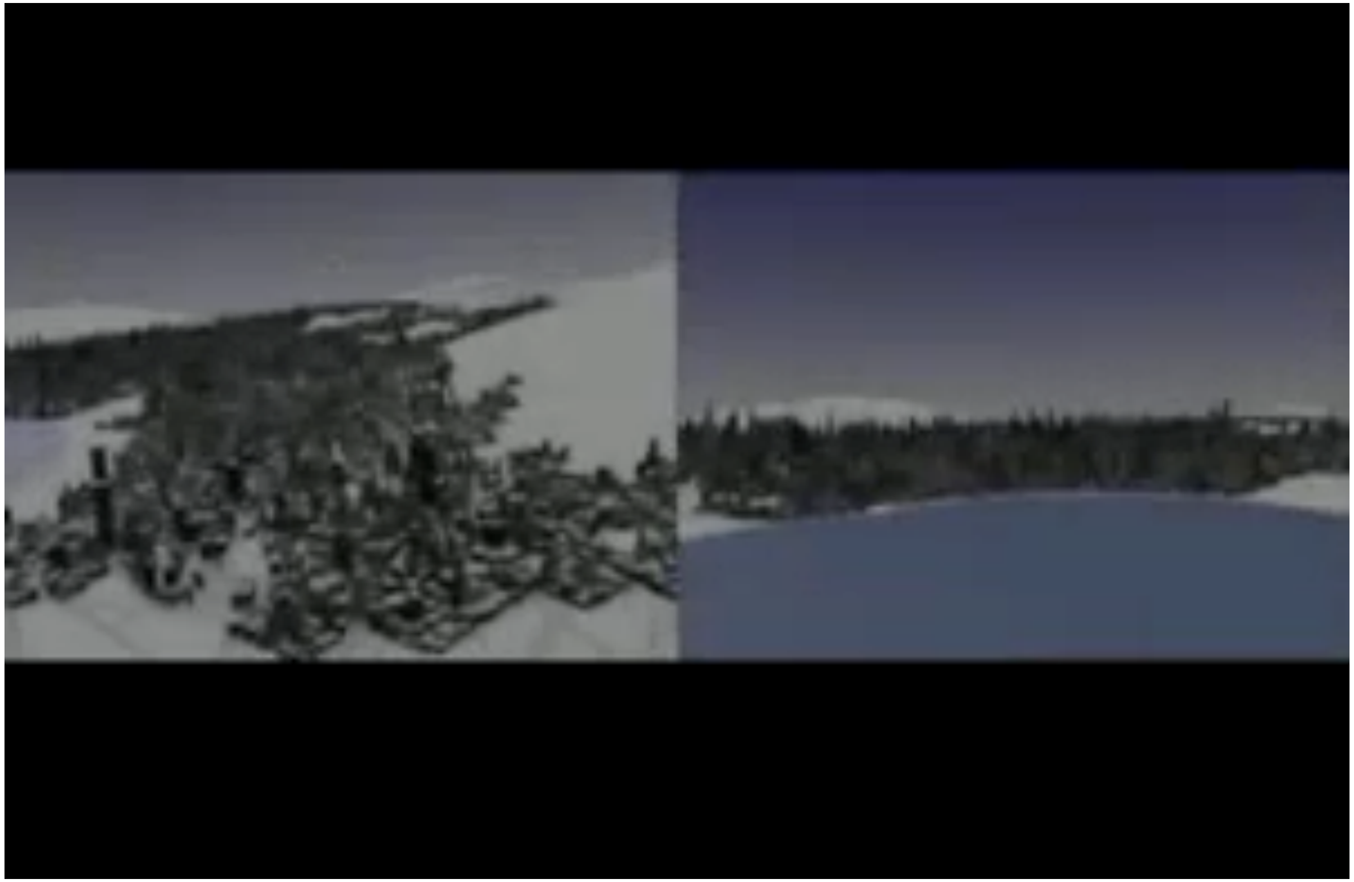


ancient Pompeii for CyberWalk

Rome rebuilt in one day!

New and old cities with CityEngine

later on, it became a spin-off of ETH Zürich

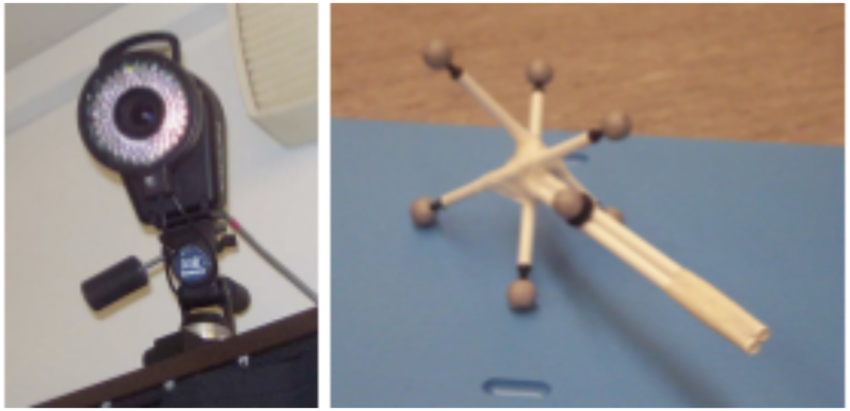


video

this procedural language allows easily to re/create …

- Zürich on its lakeshore as “Manhattan”
- ancient Pompeii for CyberWalk

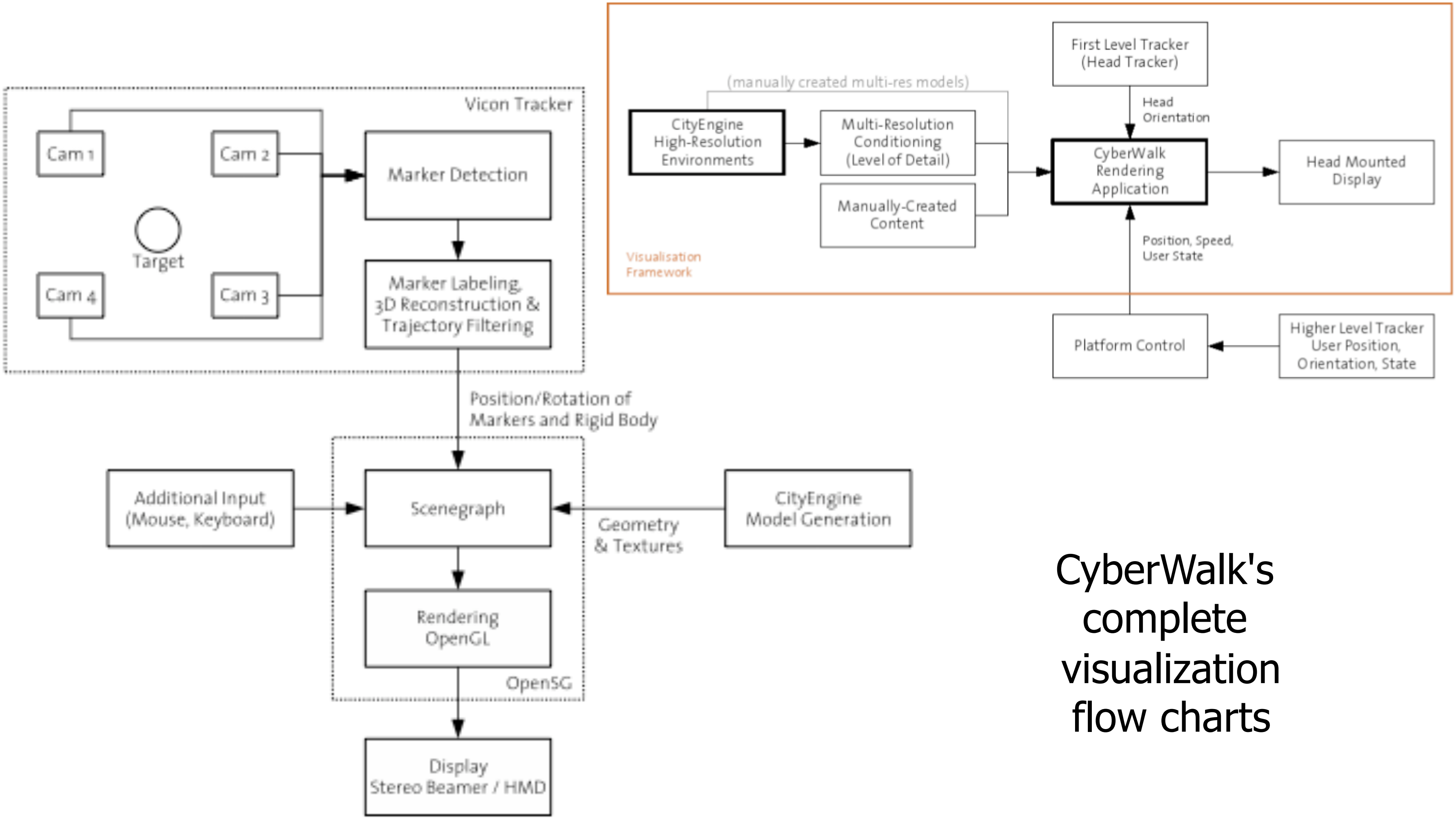
Walker tracking by Vicon



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

emulating a tracked HMD

Integration with VR visualization



Vicon Tracker
Cam 1
Cam 2
Target
Cam 4
Cam 3
Marker Detection
Marker Labeling, 3D Reconstruction & Trajectory Filtering
Position/Rotation of Markers and Rigid Body
Additional Input (Mouse, Keyboard)
Scenegraph
Geometry & Textures
CityEngine Model Generation
Rendering OpenGL
OpenSG
Display Stereo Beamer / HMD

(manually created multi-res models)
CityEngine High-Resolution Environments
Multi-Resolution Conditioning (Level of Detail)
Manually-Created Content
First Level Tracker (Head Tracker)
Head Orientation
CyberWalk Rendering Application
Head Mounted Display
Position, Speed, User State
Visualisation Framework
Platform Control
Higher Level Tracker User Position, Orientation, State

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 1-D 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)

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

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

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

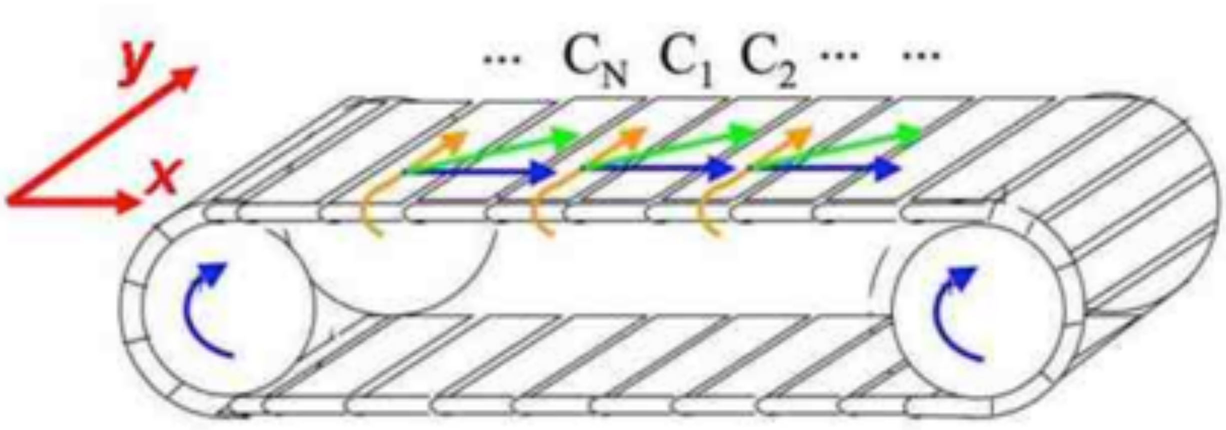
- control gains chosen so as to have stability and only real poles/zeros (≈ no oscillating transients)

remove this integrator considering $V_w(s)$ as input (constant accelerations cannot be sustainable)

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

Unmodeled dynamics

omnidirectional platform



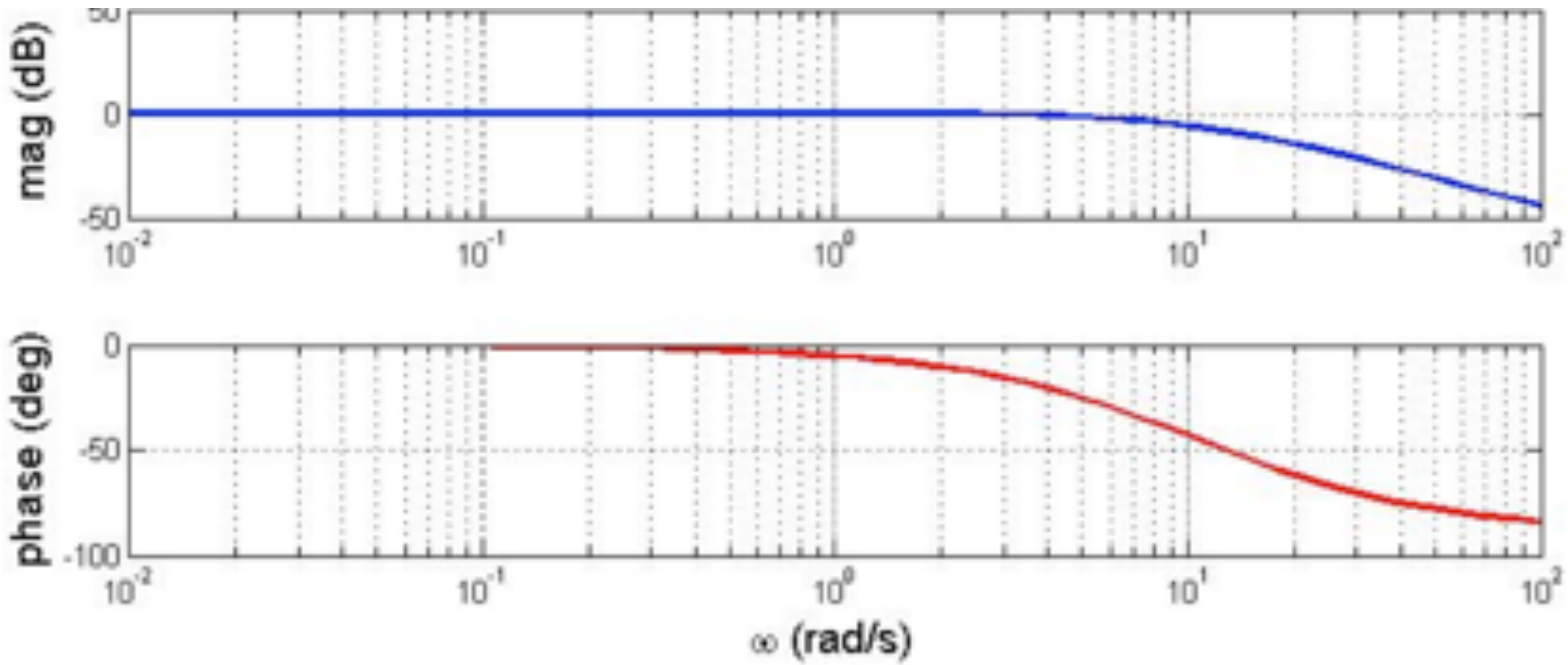
not critical in Y direction (up to 50 Hz ≈ 300 rad/s, $\frac{V_c(s)}{V_{cmd}(s)} = 1$ is ok)

needs identification in X direction, due to the larger inertia

Design steps 3 & 4
omnidirectional platform

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

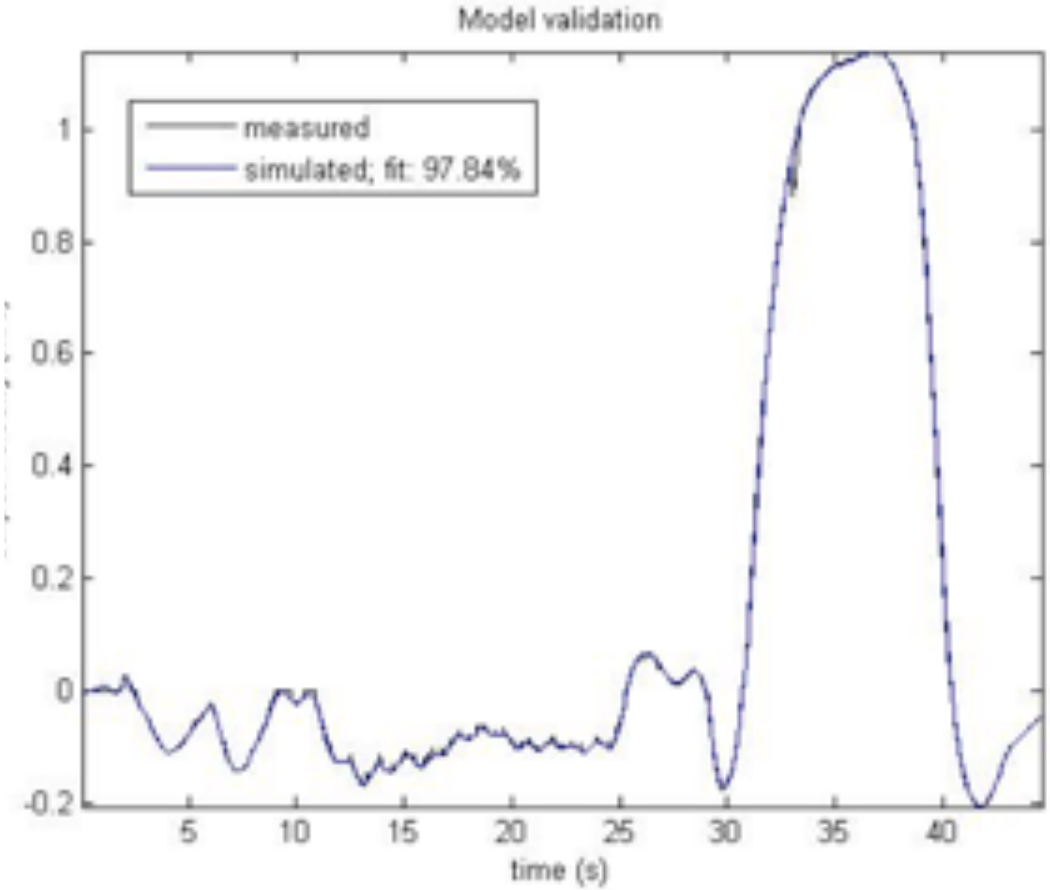
$$\frac{V_c(s)}{V_{cmd}(s)} = 1 \quad \Rightarrow \quad \frac{V_c(s)}{V_{cmd}(s)} = \frac{1.0275}{1+0.093967\,s}$$



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

Design step 5
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

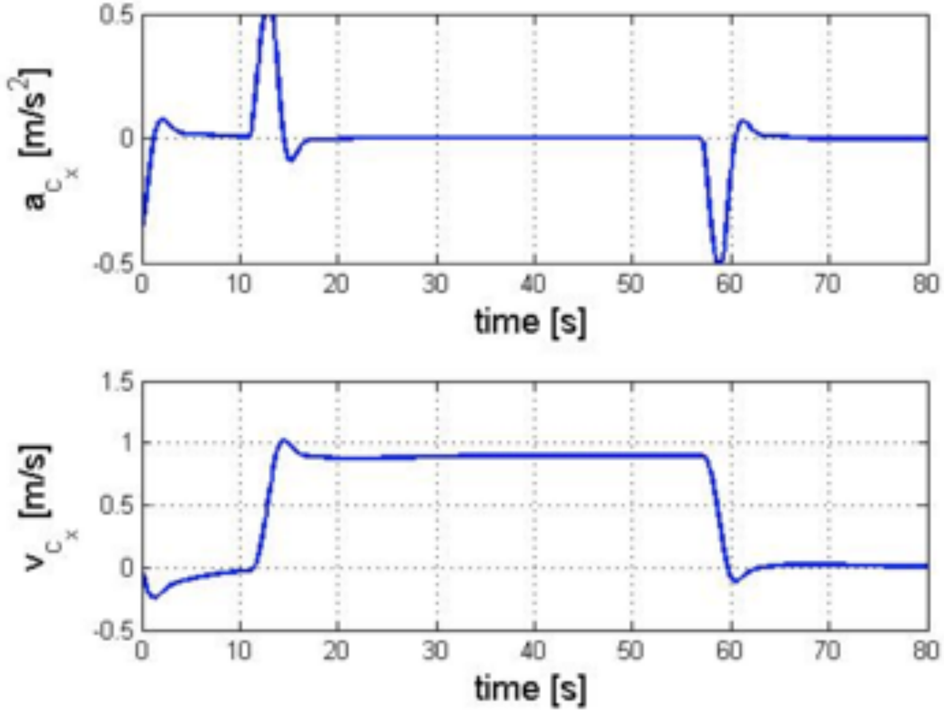
set actual control gains, with perceptual constraints

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

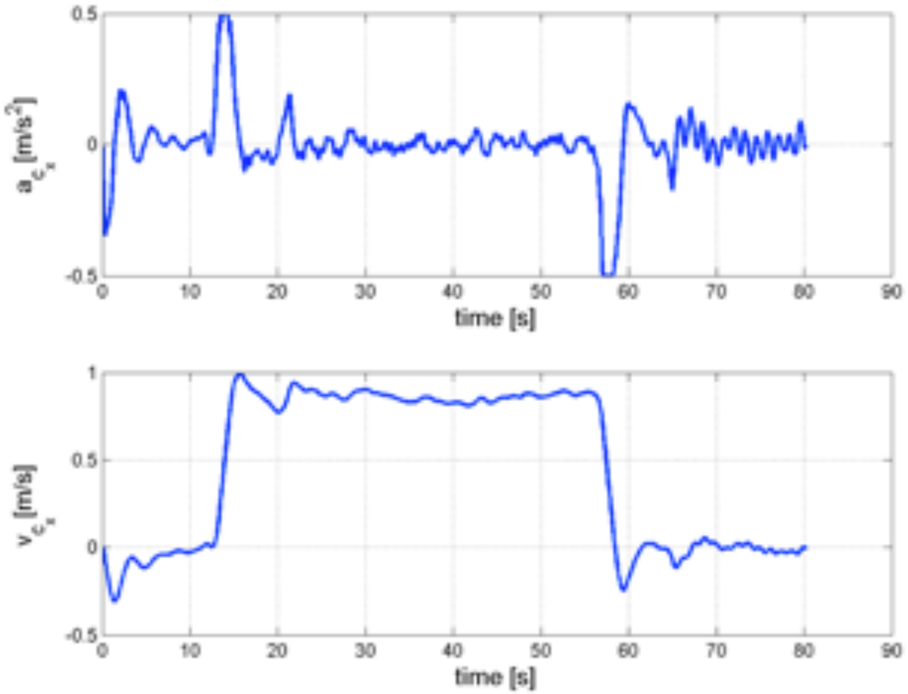
max acceleration = 0.5 m/s^2

max jerk = 1.2 m/s^3

simulation



experiment



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

The need of tuning…

video

CyberWalk Workshop
(at project end in April 2008)

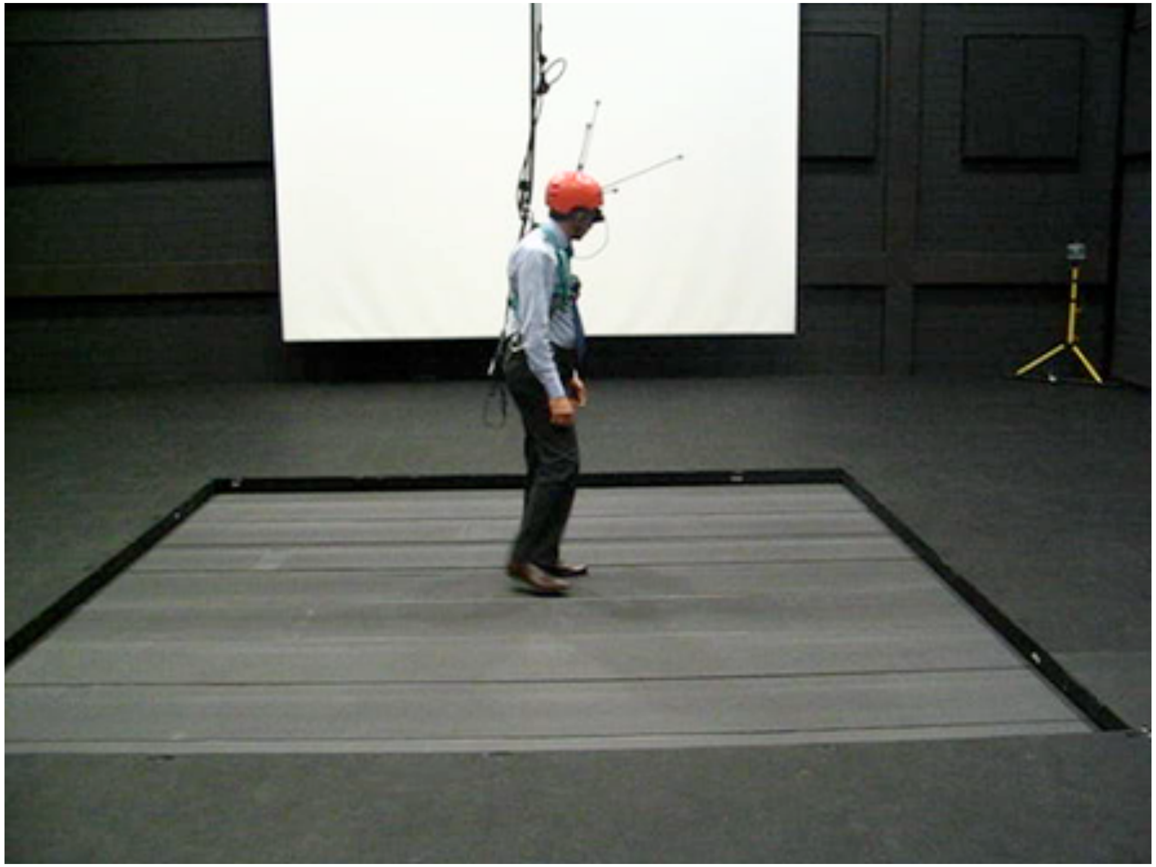
video

CyberWalk dissemination

(National Geographic video)

video

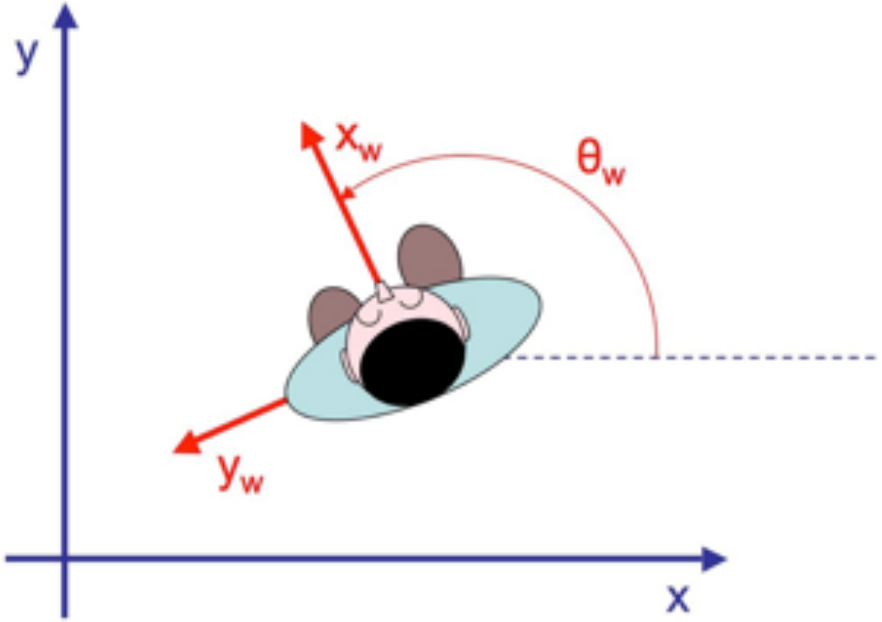
Need for further improvement...



video

Selective control gains
based on walker orientation

- basic control design takes "equal" gains in X, Y
    - axes are mechanically decoupled (1-D 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 to Vicon



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

(same for y direction)

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

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

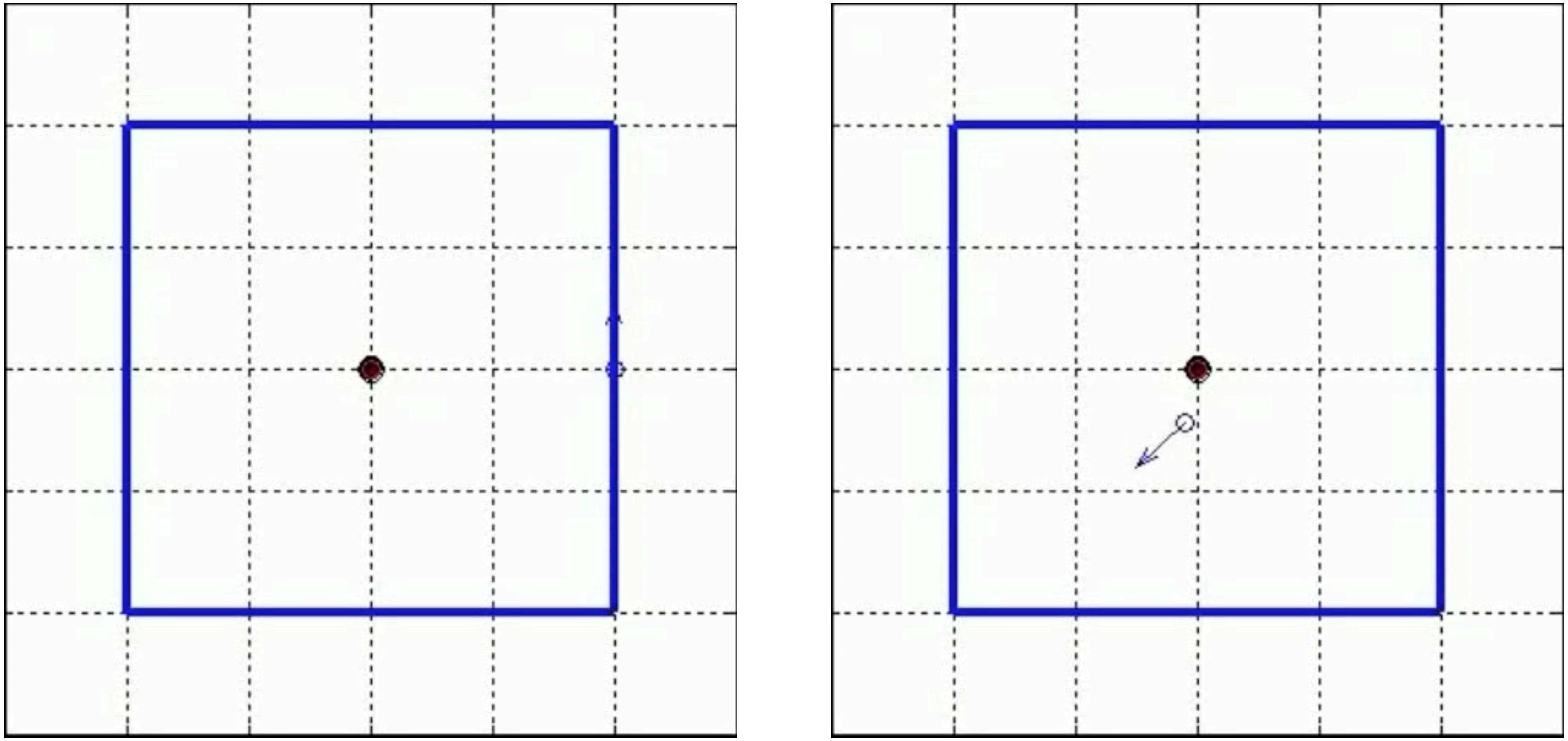
$$R(\theta_w) = \begin{bmatrix} \cos\theta_w & -\sin\theta_w \\ \sin\theta_w & \cos\theta_w \end{bmatrix}$$

Simulation

selective control gains strategy

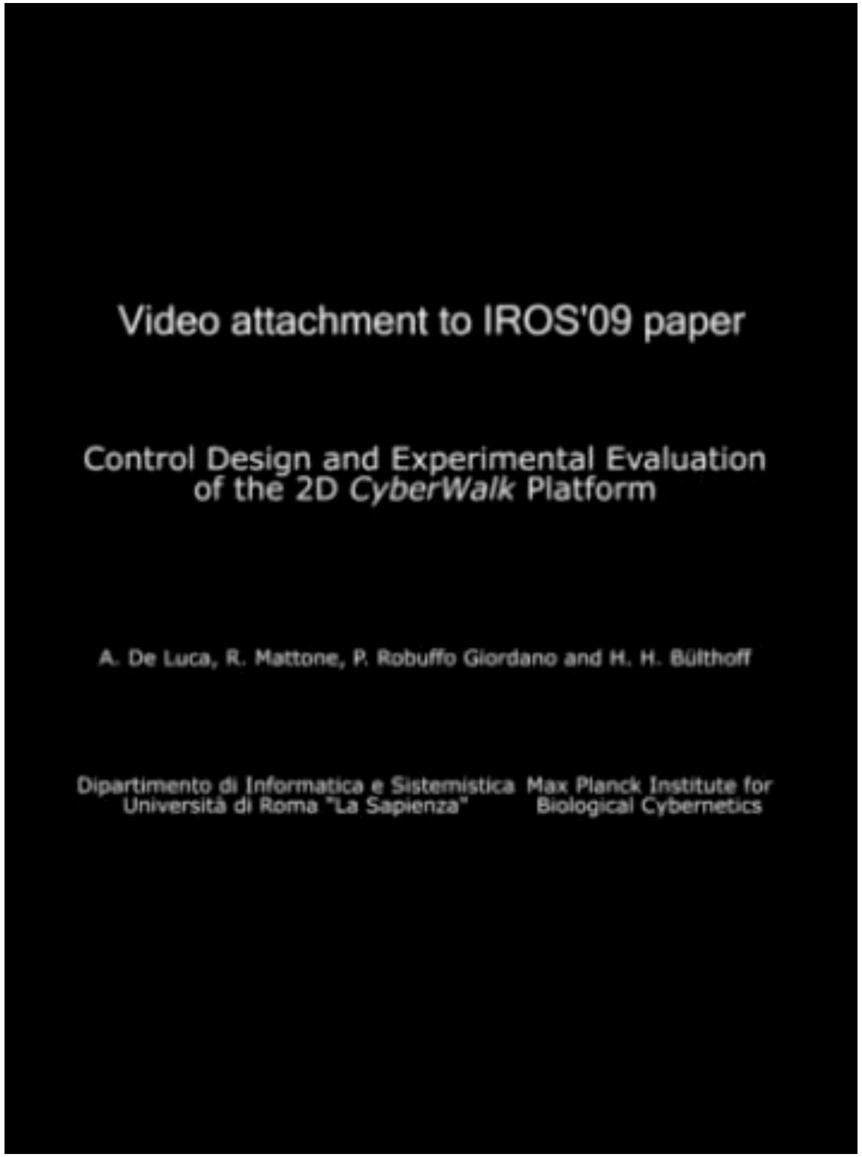
video

video



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

Latest experiments



Video attachment to IROS'09 paper

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

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video

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)

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