SIGGRAPH
ASIA 2018
TOKYO

Christian Richardt

# Motion-Aware Displays

SIGGRAPH Asia Course on Cutting-Edge VR/AR Display Technologies

CAMERA
Centre for the Analysis of Motion,
Entertainment Research and Applications

UNIVERSITY OF
BATH

richardt.name
c_richardt

# Schedule

| Start | Topic | Speaker |
|---|---|---|
| 14:15 | Introduction | George Alex Koulieris |
| 14:30 | Multi-focal displays | George Alex Koulieris |
| 15:05 | Near-eye varifocal AR | Kaan Akşit |
| 15:50 | Coffee break | |
| 16:00 | HDR-enabled displays | Rafał Mantiuk |
| 16:45 | Motion-aware displays | Christian Richardt |
| 17:30 | Demos & Summary | All presenters |

# Why care about motion?

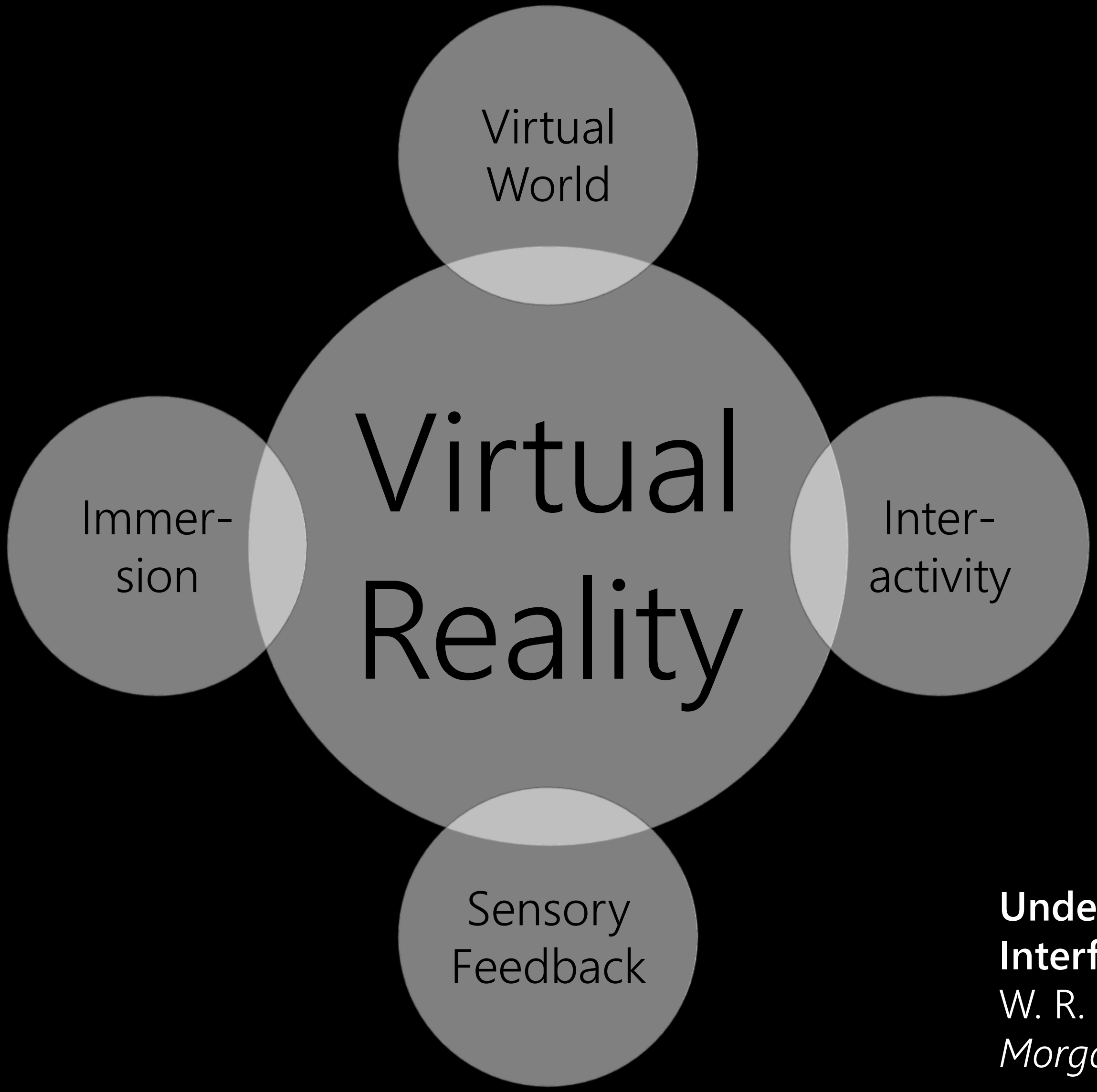
**The world's first VR HMD** by Ivan Sutherland (1968): Miniature CRTs, head tracking with mechanical sensors (in the video, "Sword of Damocles") or ultrasonic sensors

- Need to track motion to generate the right images:
  - head motion
  - hand motion
  - full-body motion
- Motion tracking enables:
  - **immersion** = the replacement of perception with virtual stimuli
  - **presence** = the sensation of "being there"

# Motion-aware displays

1. Perception of immersion
2. Tracking in VR and AR
3. Hand input devices
4. Motion capture

# Virtual reality experiences




**Understanding Virtual Reality: Interface, Application, and Design**
W. R. Sherman & A. B. Craig
*Morgan Kaufmann Publishers*, 2003

# Immersion vs Presence

- **Immersion** is an objective notion which can be defined as the sensory stimuli coming from a device, for example a data glove
- Measurable and comparable between devices

- **Presence** is a subjective phenomenon, personal experiences in an immersive environment
- Subjective feeling of being there

**A note on presence terminology**
M. Slater
*Presence Connect*, 2003, 3:3

Slide adapted from Zerrin Yumak

# Immersion

- sensation of being in another environment
- **Mental immersion:**
  - a movie, game or a novel might immerse you too
  - suspension of disbelief, state of being deeply engaged
- **Physical immersion:**
  - bodily entering into a medium
  - synthetic stimulus of the body's senses via the use of technology

Slide adapted from Zerrin Yumak

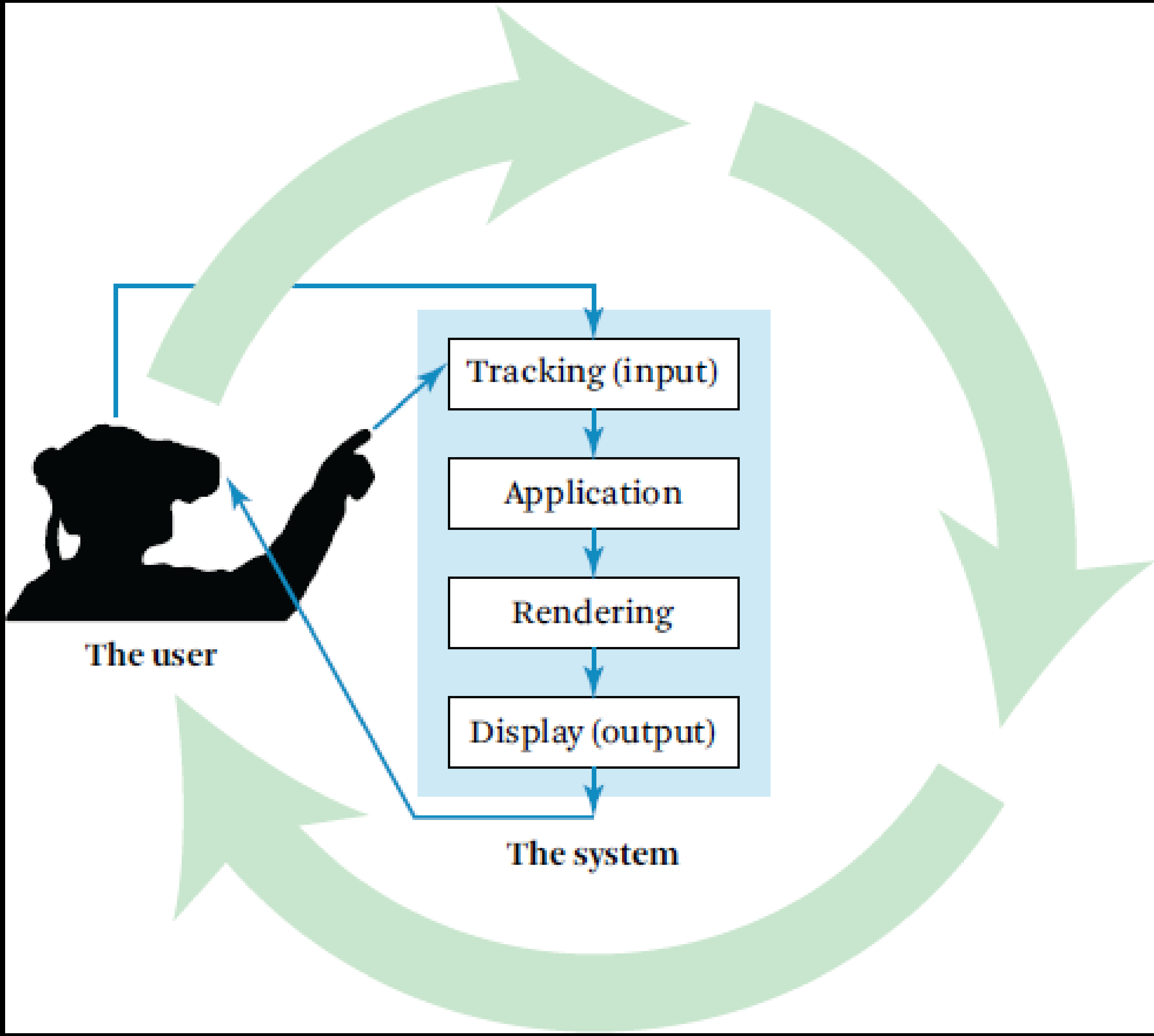
# Self-embodiment

- Perception that the user has a body within the virtual world
- The presence of a virtual body can be quite compelling
  - even when that body does not look like one's own body
  - effective for teaching empathy by "walking in someone else's shoes" and can reduce racial bias
- Whereas body shape and colour are not so important, <u>motion is extremely important</u>
- Presence can be broken when visual body motion does not match physical motion

**Putting Yourself in the Skin of a Black Avatar Reduces Implicit Racial Bias**
T. C. Peck, S. Seinfeld, S. M. Aglioti & M. Slater
*Consciousness and Cognition*, 2013, 22(3), 779–787

Slide adapted from Zerrin Yumak

# VR system input–output cycle

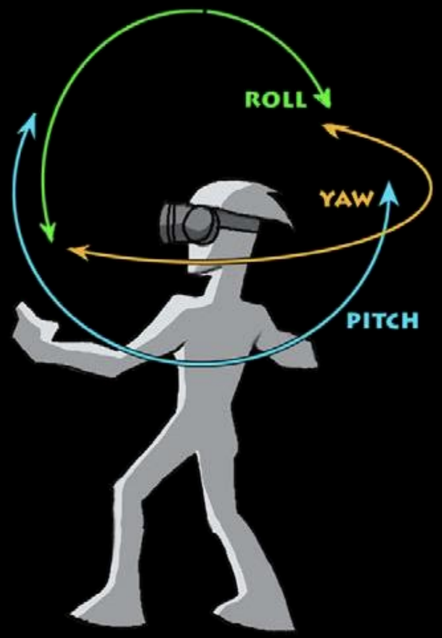



**Scene-Motion- and Latency-Perception Thresholds for Head-Mounted Displays**
J. J. Jerald
*PhD Thesis*, UNC Chapel Hill, 2009

# Tracking degrees of freedom (DoF)

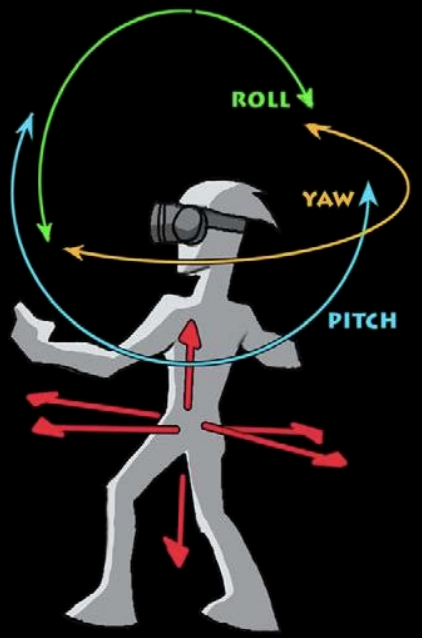
## 3 degrees of freedom (3-DoF)

- “In which direction am I looking”
- Detect rotational head movement
- Look around the virtual world from a fixed point




## 6 degrees of freedom (6-DoF)

- “Where am I and in which direction am I looking”
- Detect rotations and translational movement
- Move in the virtual world like in the real world




Slide adapted from Qualcomm Technologies, Inc.

# Tracking technologies

- Mechanical:
  - e.g. physical linkage
- Electromagnetic:
  - e.g. magnetic sensing
- Inertial:
  - e.g. accelerometers, MEMs
- Acoustic:
  - e.g. ultrasonic
- Optical:
  - computer vision
- Hybrid:
  - combination of technologies

contact-less tracking

Slide adapted from Bruce Thomas & Mark Billinghurst

# Mechanical tracking

- Idea: mechanical arms with joint sensors
- Advantages:
  - high accuracy
  - low jitter
  - low latency
- Disadvantages:
  - cumbersome
  - limited range
  - fixed position

Ivan Sutherland's Sword of Damocles (1968)

MicroScribe (2005)

Slide adapted from Bruce Thomas & Mark Billinghurst

# Magnetic tracking

- Idea: measure difference in current between a magnetic transmitter and a receiver
- Advantages:
  - 6-DoF, robust & accurate
  - no line of sight needed
- Disadvantages:
  - limited range, noisy
  - sensitive to metal
  - expensive

**Razer Hydra (2011)**
Magnetic source with two wired controllers
short range (<1 m), precision of 1 mm and 1°
62 Hz sampling rate, <50 ms latency

**Magic Leap One (2018)**
Transmitter generates 3 orthogonal magnetic fields; unknown specs

Slide adapted from Bruce Thomas & Mark Billinghurst

# Inertial tracking

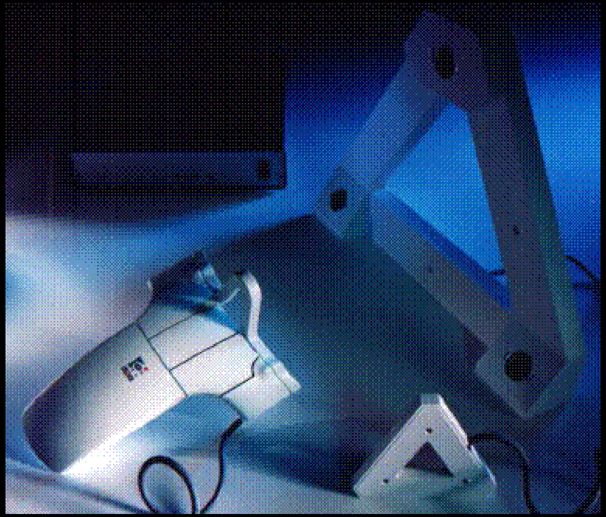
- Idea: Measuring linear and angular orientation rates (accelerometer/gyroscope)
- Advantages:
  - no transmitter, wireless
  - cheap + small
  - high sample rate
- Disadvantages:
  - drift + noise
  - only 3-DoF

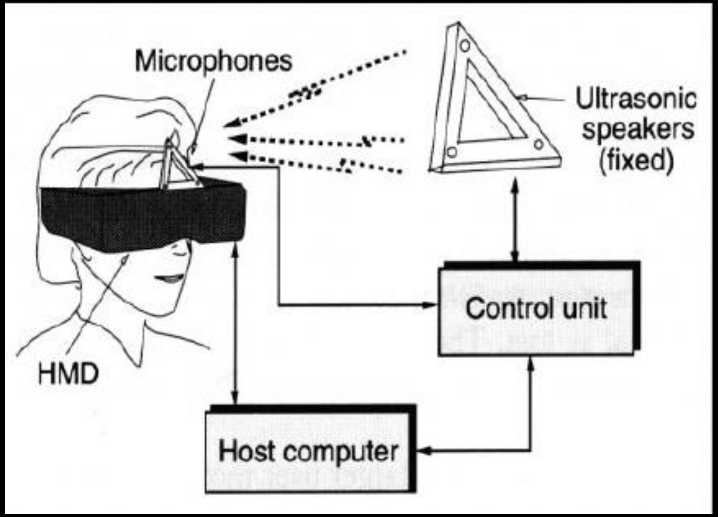
**Google Daydream View (2017)**
relies on the phone for processing and tracking
3-DoF rotational only tracking of phone + controller

Slide adapted from Bruce Thomas & Mark Billinghurst

# Acoustic tracking

- Idea: time-of-flight or phase-coherent sound waves
- Advantages:
  - small + cheap
- Disadvantages:
  - only 3-DoF
  - low resolution
  - low sampling rate
  - requires line-of-sight
  - affected by environment (pressure, temperature)






**Logitech 3D Head Tracker (1992)**
Transmitter has 3 ultrasonic speakers, 30 cm apart; receiver has 3 mics
range: ~1.5 m, accuracy: 0.1° orientation, 2% distance
50 Hz update, 30 ms latency

Slide adapted from Bruce Thomas & Mark Billinghurst

# Optical tracking

- Idea: image processing and computer vision to the rescue
- often using infrared light, retro-reflective markers, multiple views
- Advantages:
  - long range, cheap
  - immune to metal
  - usually very accurate
- Disadvantages:
  - requires markers, line of sight
  - can have low sampling rate


**Microsoft Kinect (2010)**
IR laser speckle projector, RGB + IR cameras
range: 1–6 m, accuracy: <5 mm
30 Hz update rate, 100 ms latency

Slide adapted from Bruce Thomas & Mark Billinghurst

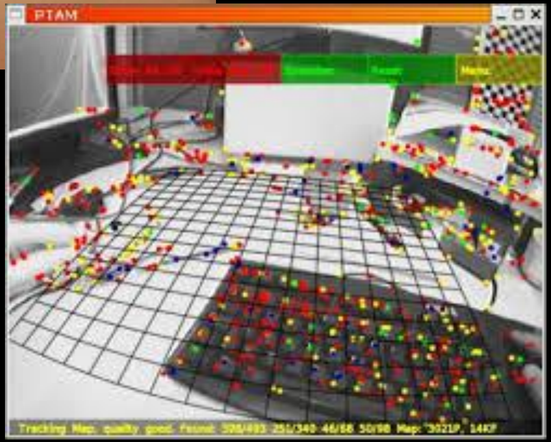
# AR optical tracking

- Marker tracking:
  - tracking known artificial images
    - e.g. ARToolKit square markers
- Markerless tracking:
  - tracking from known features in real world
    - e.g. Vuforia image tracking
- Unprepared tracking:
  - in unknown environments
    - e.g. SLAM (simultaneous localisation and mapping)

devfun-lab.com

mobilegeeks.de

PTAM




Slide adapted from Bruce Thomas & Mark Billinghurst

# Hybrid tracking

- Idea: multiple technologies overcome limitations of each one
- A system that utilizes two or more position/orientation measurement technologies (e.g. inertial + visual)
- Advantages:
  - robust
  - reduce latency
  - increase accuracy
- Disadvantages:
  - more complex + expensive

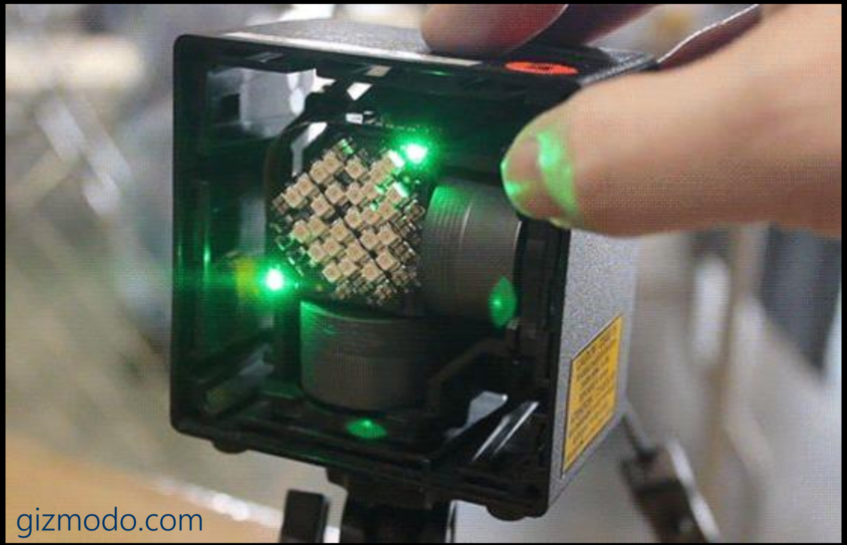
digitaltrends.com

**Apple ARKit (2017), Google ARCore (2018)**
visual-inertial odometry – combine inertial motion sensing with feature point tracking

Slide adapted from Bruce Thomas & Mark Billinghurst

# Example: Vive Lighthouse tracking

- Outside-in hybrid tracking:
  - 2 base stations: each with 2 laser scanners, LED array
- Headworn/handheld sensors:
  - 37 photo sensors in HMD, 17 in hand
  - additional IMU sensors (500 Hz)
- Performance:
  - tracking fuses sensor samples at 250 Hz
  - 2 mm RMS accuracy
  - large area: $5 \times 5\ m^2$ range
- See: https://youtu.be/xrsUMEbLtOs



gizmodo.com


slashgear.com

Slide adapted from Bruce Thomas & Mark Billinghurst

# Hand input devices

- Devices that integrate hand input into VR:
  - world-grounded input devices
  - non-tracked handheld controllers
  - tracked handheld controllers
  - hand-worn devices
  - hand tracking

digitaltrends.com

Slide adapted from Bruce Thomas & Mark Billinghurst

# World-grounded hand input devices

- Devices constrained or fixed in the real world
  - e.g. joysticks, steering wheels
- Not ideal for VR
  - constrains user motion
- Good for VR vehicle metaphor, location-based entertainment
  - e.g. driving simulators, Disney's "Aladdin's Magic Carpet Ride"

aliexpress.com

realityprime.com

Slide adapted from Bruce Thomas & Mark Billinghurst

# Non-tracked handheld controllers

- Devices held in hand
  - buttons
  - joysticks
  - game controllers
- Traditional video game controllers
  - e.g. Xbox controller

**Bottomless Joystick**
katsumotoy.com/bj/


techadvisor.co.uk

Slide adapted from Bruce Thomas & Mark Billinghurst

# Tracked handheld controllers

- Handheld controller with 6-DoF tracking
  - combines button/joystick/ trackpad input plus tracking
- One of the best options for VR applications
  - physical prop enhancing VR presence
  - providing proprioceptive, passive haptic touch cues
  - direct mapping to real hand motion


HTC Vive controller

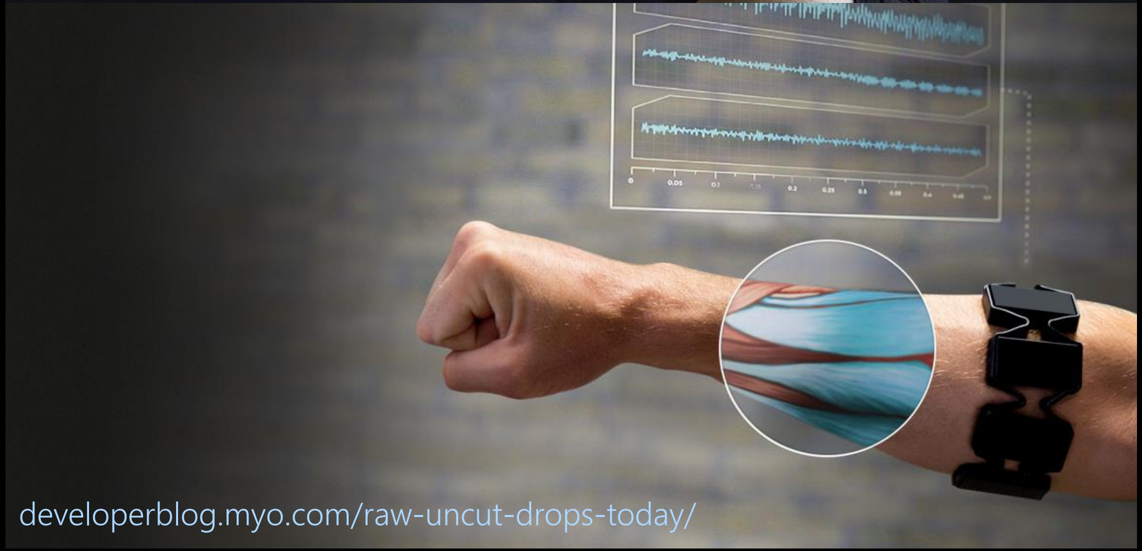
Oculus Touch

Slide adapted from Bruce Thomas & Mark Billinghurst

# Hand-worn devices

- Devices worn on hands/arms
  - e.g. glove, EMG sensors, rings
- Advantages:
  - natural input with potentially rich gesture interaction
  - hands can be held in comfortable positions
    - no line-of-sight issues
  - hands and fingers can fully interact with real objects

virtualrealitytimes.com



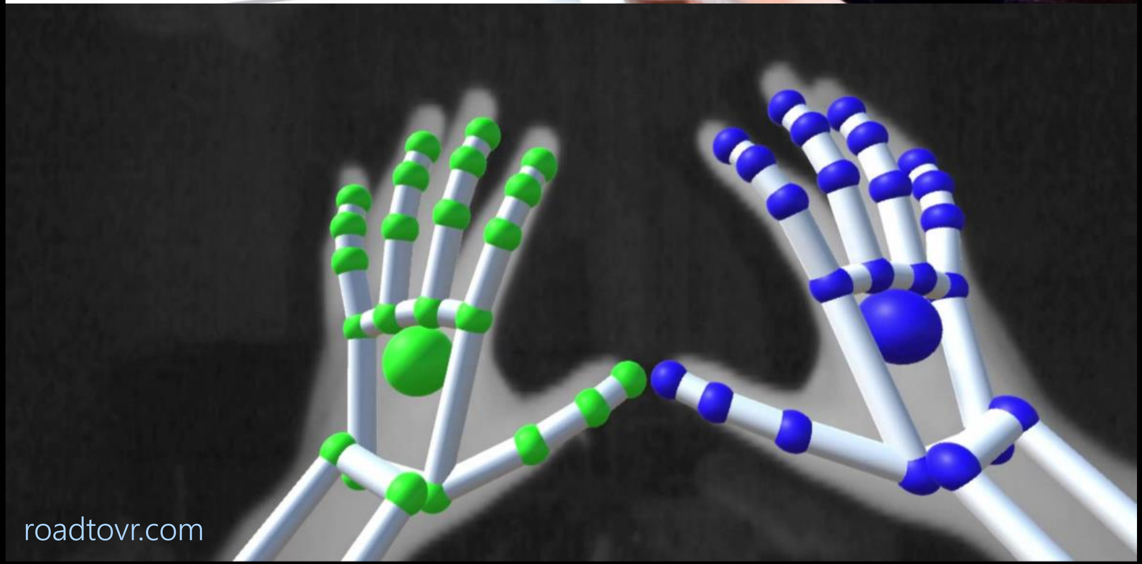
developerblog.myo.com/raw-uncut-drops-today/

Slide adapted from Bruce Thomas & Mark Billinghurst

# Hand tracking

- Using computer vision to track bare hand input
- Creates compelling sense of presence, natural interaction
- Advantages:
  - least intrusive, purely passive
  - hands-free tracking, so can interact freely with real objects
  - low power requirements, cheap
  - more ubiquitous, works outdoors

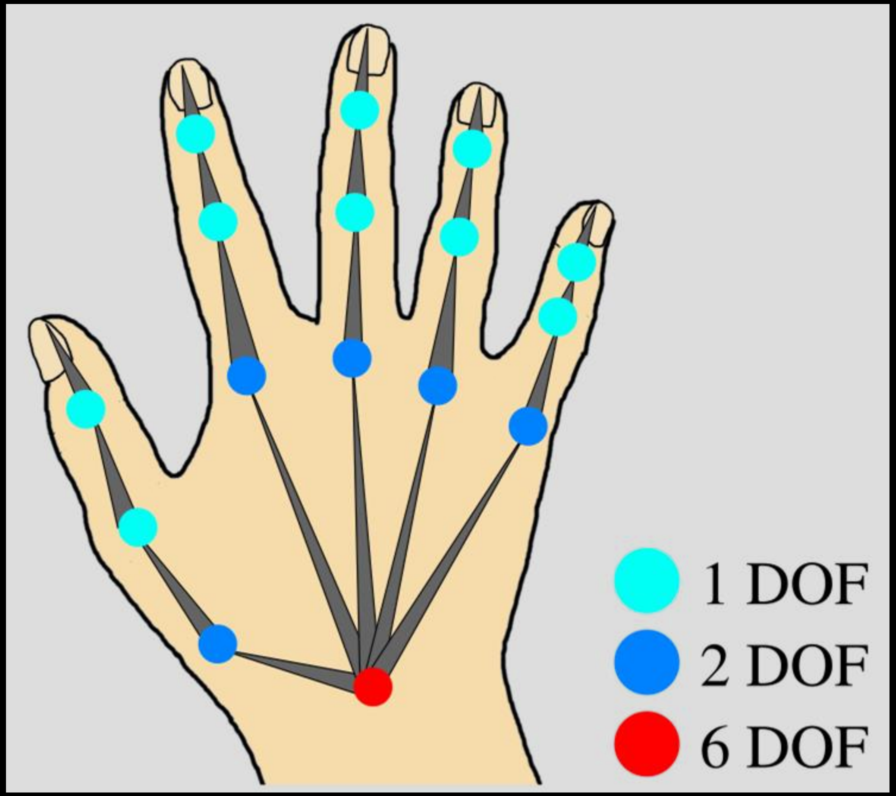
NimbleVR


roadtovr.com

Slide adapted from Bruce Thomas & Mark Billinghurst, Franziska Mueller

# Case study: Egocentric hand tracking

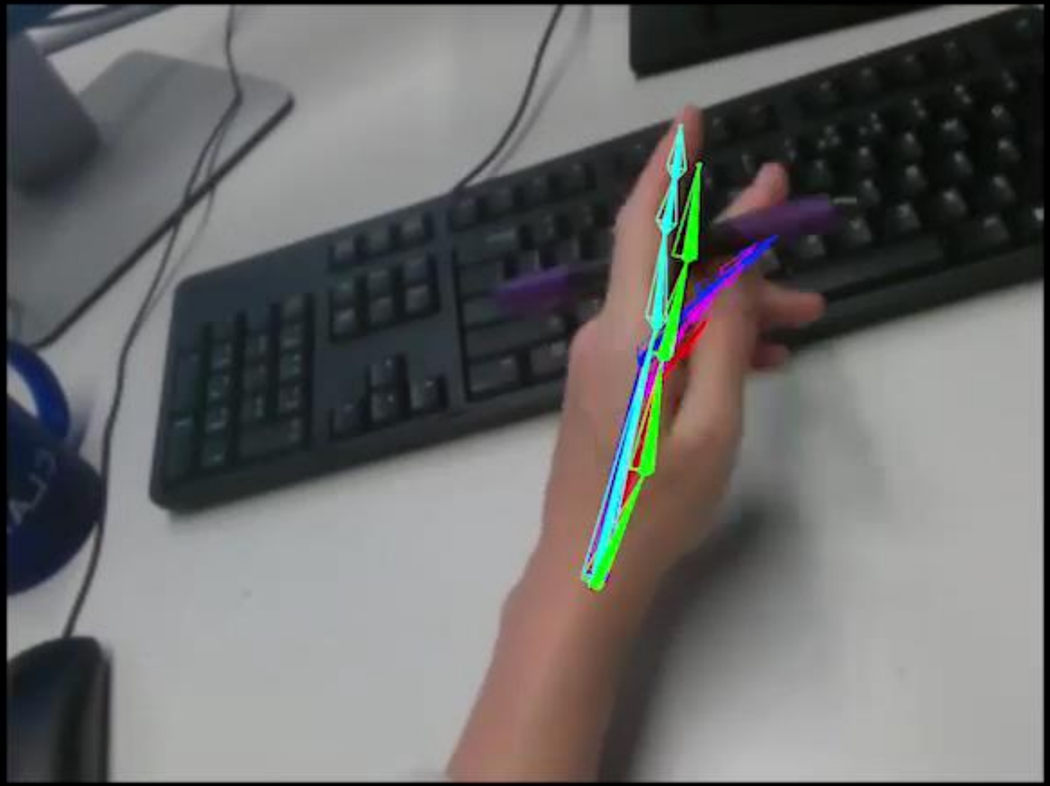
- **Goal:** reconstruct full hand pose (global transform + joint angles) using a single body-mounted camera
- Robust to:
  - fast and complex motions
  - background clutter
  - occlusions by arbitrary objects as well as the hand itself
  - self-similarities of hands
  - fairly uniform colour
- In real time (>30 Hz)

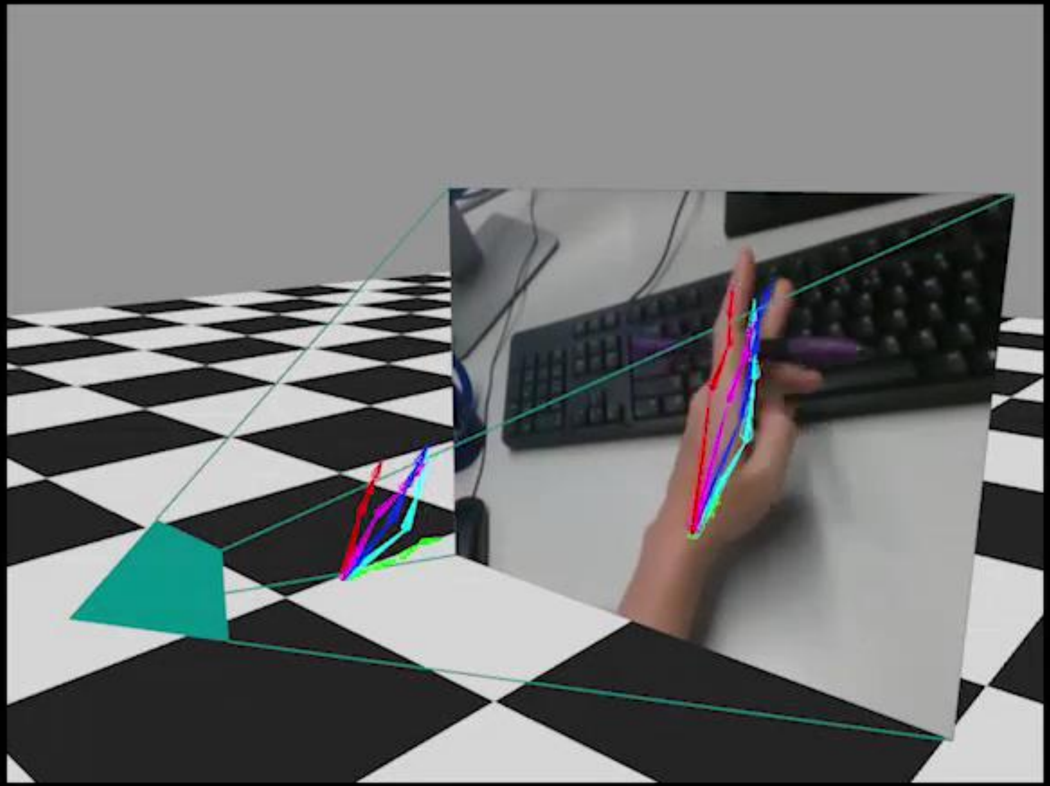





Slide adapted from Franziska Mueller

# Egocentric hand tracking





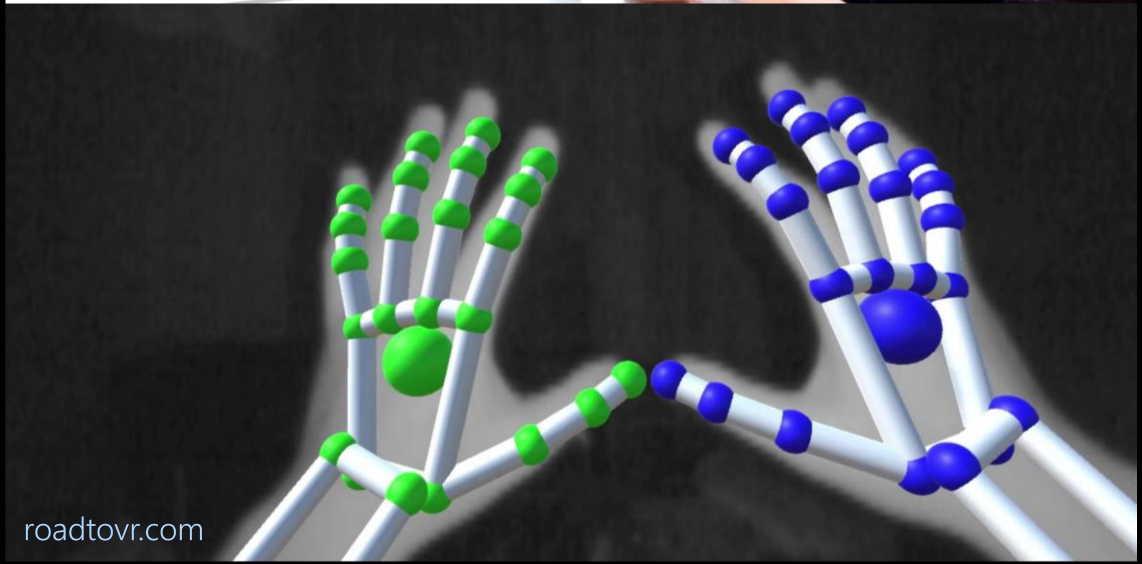
https://youtu.be/0wH0b9MdjPI?t=4

**GANerated Hands for Real-time 3D Hand Tracking from Monocular RGB**
F. Mueller, F. Bernard, O. Sotnychenko, D. Mehta, S. Sridhar, D. Casas & C. Theobalt
*CVPR*, 2018

# Remaining challenges of hand tracking

- Robust results out of the box:
  - interacting with unknown objects
  - two hands simultaneously
  - no explicit model fitting
- Usability challenges:
  - not having sense of touch
  - line of sight required to sensor
  - fatigue from holding hands in front of sensor

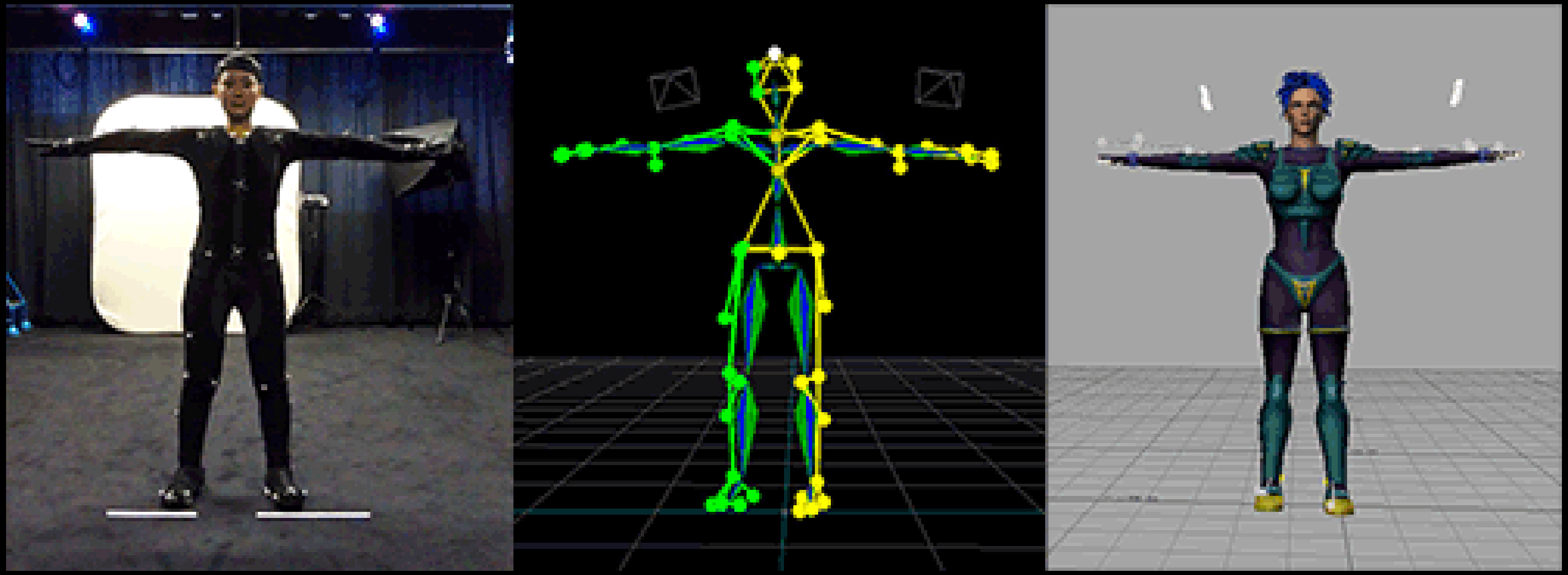
NimbleVR


roadtovr.com

Slide adapted from Bruce Thomas & Mark Billinghurst

# Full-body tracking

- Adding full-body input into VR:
  - creates illusion of self-embodiment
  - significantly enhances sense of presence



protchenko.info

Slide adapted from Bruce Thomas & Mark Billinghurst

# Camera-based motion capture

- Use multiple cameras (8+) with infrared (IR) LEDs
- Retro-reflective markers on body clearly reflect IR light
- For example Vicon, OptiTrack:
  - very accurate: <1 mm error
  - very fast:
    - 100–360 Hz sampling rate
    - <10 ms latency
  - each marker needs to be seen by at least two cameras


Vicon


OptiTrack

digitalcinema.com.ua

Slide adapted from Bruce Thomas & Mark Billinghurst

SIGGRAPH ASIA 2016 MACAO

# EgoCap: Egocentric Marker-less Motion Capture with Two Fisheye Cameras


Helge Rhodin[1] Christian Richardt[123] Dan Casas[1],

Eldar Insafutdinov[1] Mohammad Shafiei[1]

Hans-Peter Seidel[1] Bernt Schiele[1] Christian Theobalt[1]

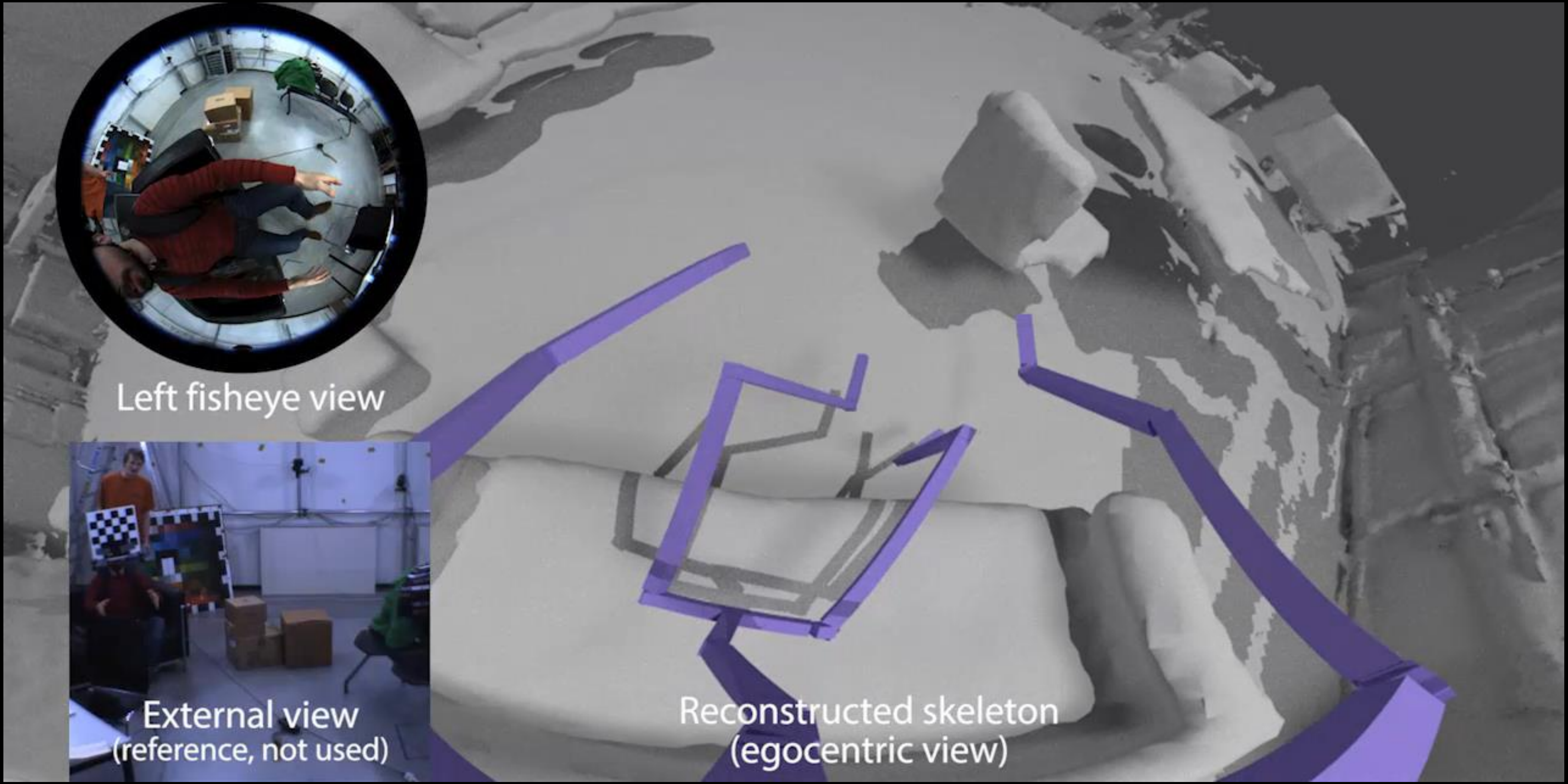
Graphics Vision & Video

[1] mpii max planck institut informatik

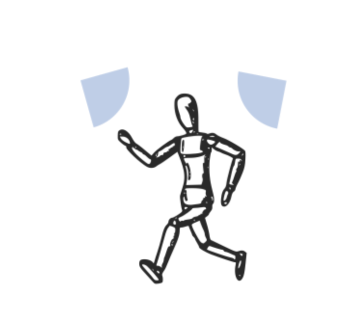
[2] intel VISUAL COMPUTING INSTITUTE

[3] UNIVERSITY OF BATH

# Embodied virtual reality

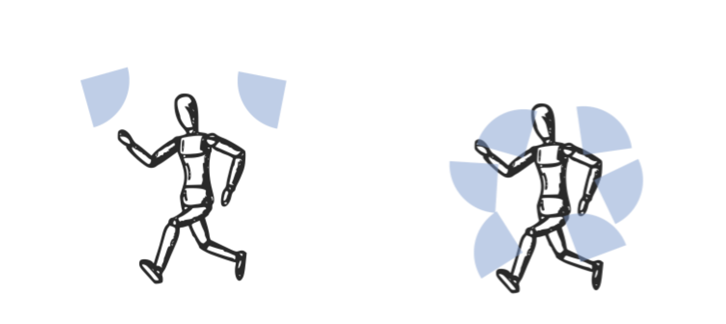


# Marker-less motion capture



| Outside-in |
|---|
| Non-intrusive |
| Limited capture volume |
| Full-body |

# Marker-less motion capture



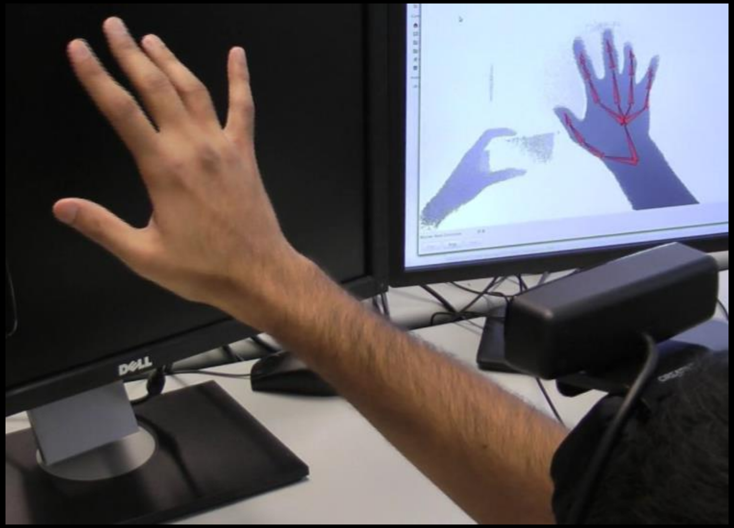
| Outside-in | Inside-out |
|---|---|
| Non-intrusive | Intrusive |
| Limited capture volume | Infinite capture volume |
| Full-body | Full-body |

[Shiratori 2011]

# Marker-less motion capture

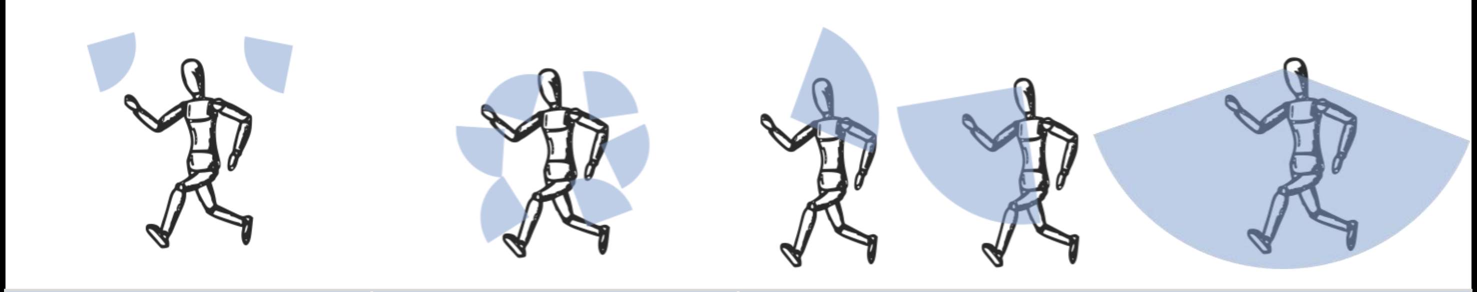
| Outside-in | Inside-out | Inside-in |
|---|---|---|
| Non-intrusive | Intrusive | Low intrusion |
| Limited capture volume | Infinite capture volume | Infinite capture volume |
| Full-body | Full-body | Partial-body |

[Jones 2011, Wang 2016]



[Sridhar 2015, …]

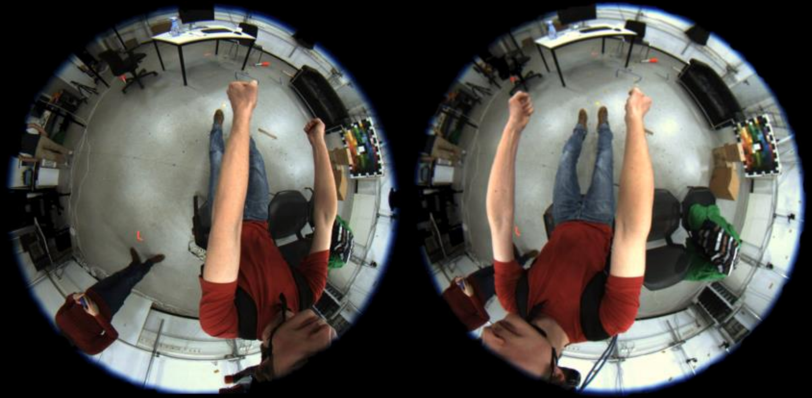
# Marker-less motion capture



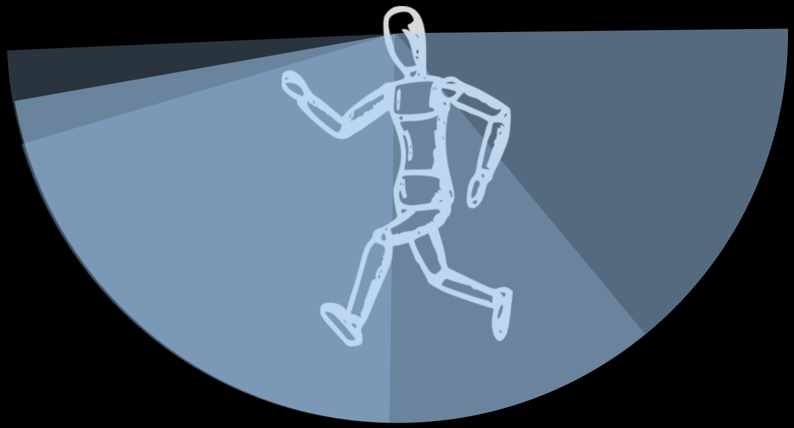
| Outside-in | Inside-out | Inside-in | EgoCap |
|---|---|---|---|
| Non-intrusive | Intrusive | Low intrusion | Low intrusion |
| Limited capture volume | Infinite capture volume | Infinite capture volume | Infinite capture volume |
| Full-body | Full-body | Partial-body | Full-body |

# Camera gear

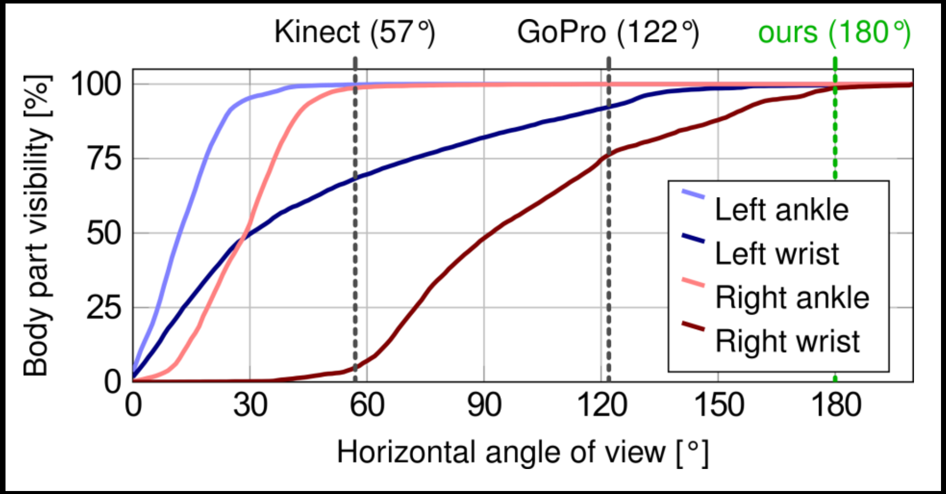
Camera extensions



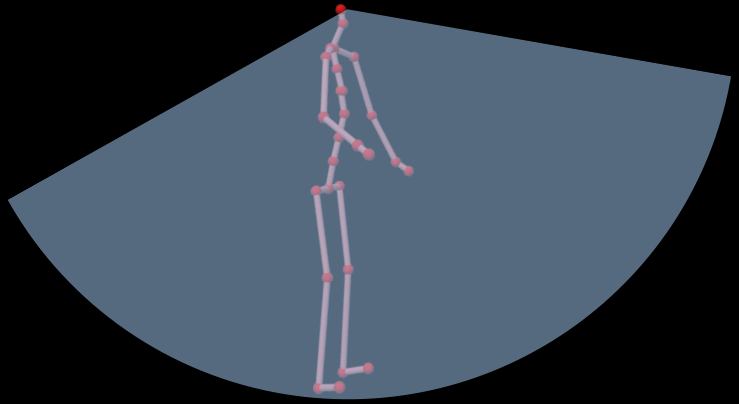
Egocentric view examples



Field of view



# Egocentric capture challenges



Camera is attached

Subject is always in view

Human pose is independent of global motion

Estimation of global motion

Moving background

Top-down view

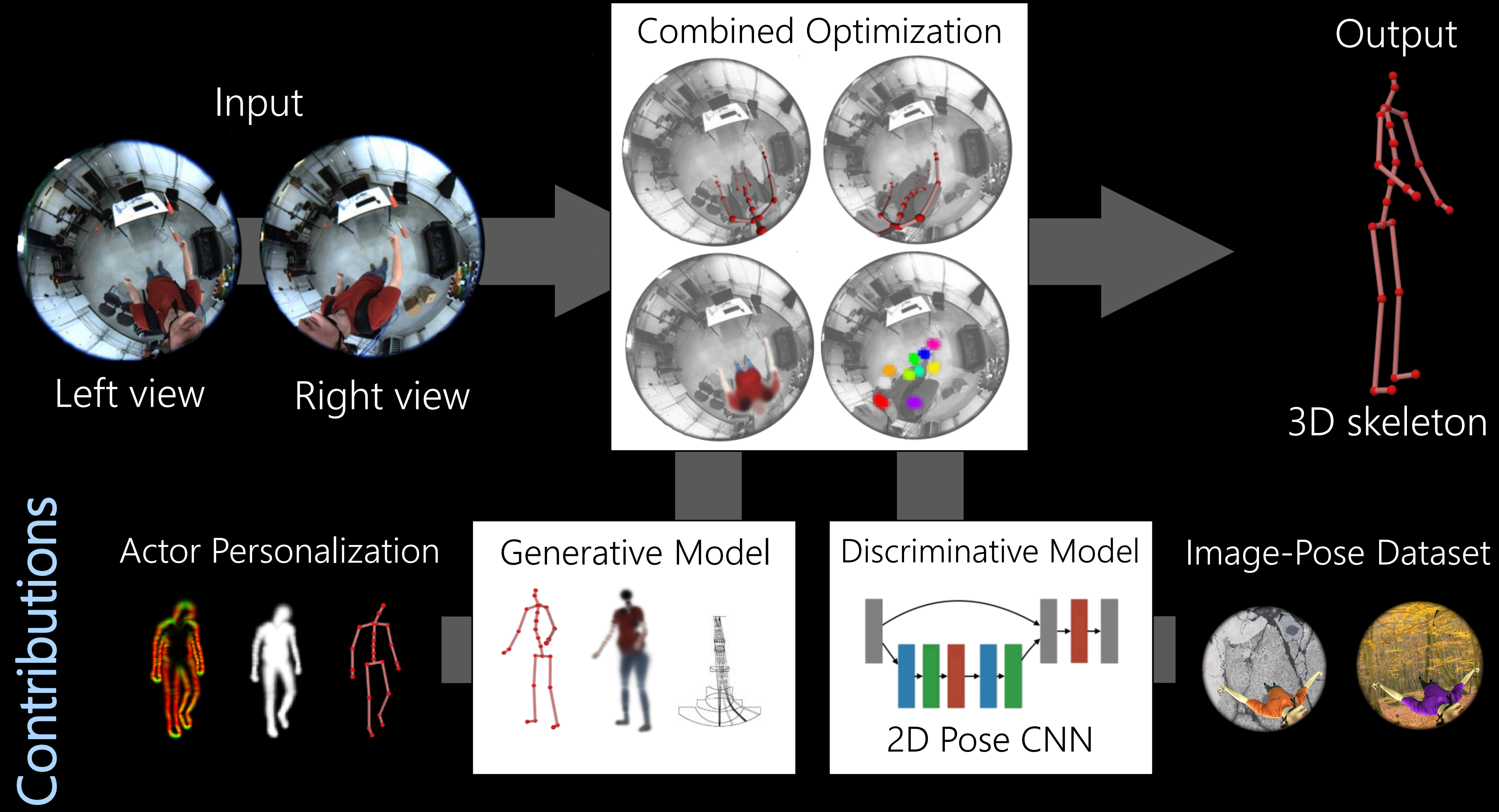
Self-occlusions

The lower body appears tiny

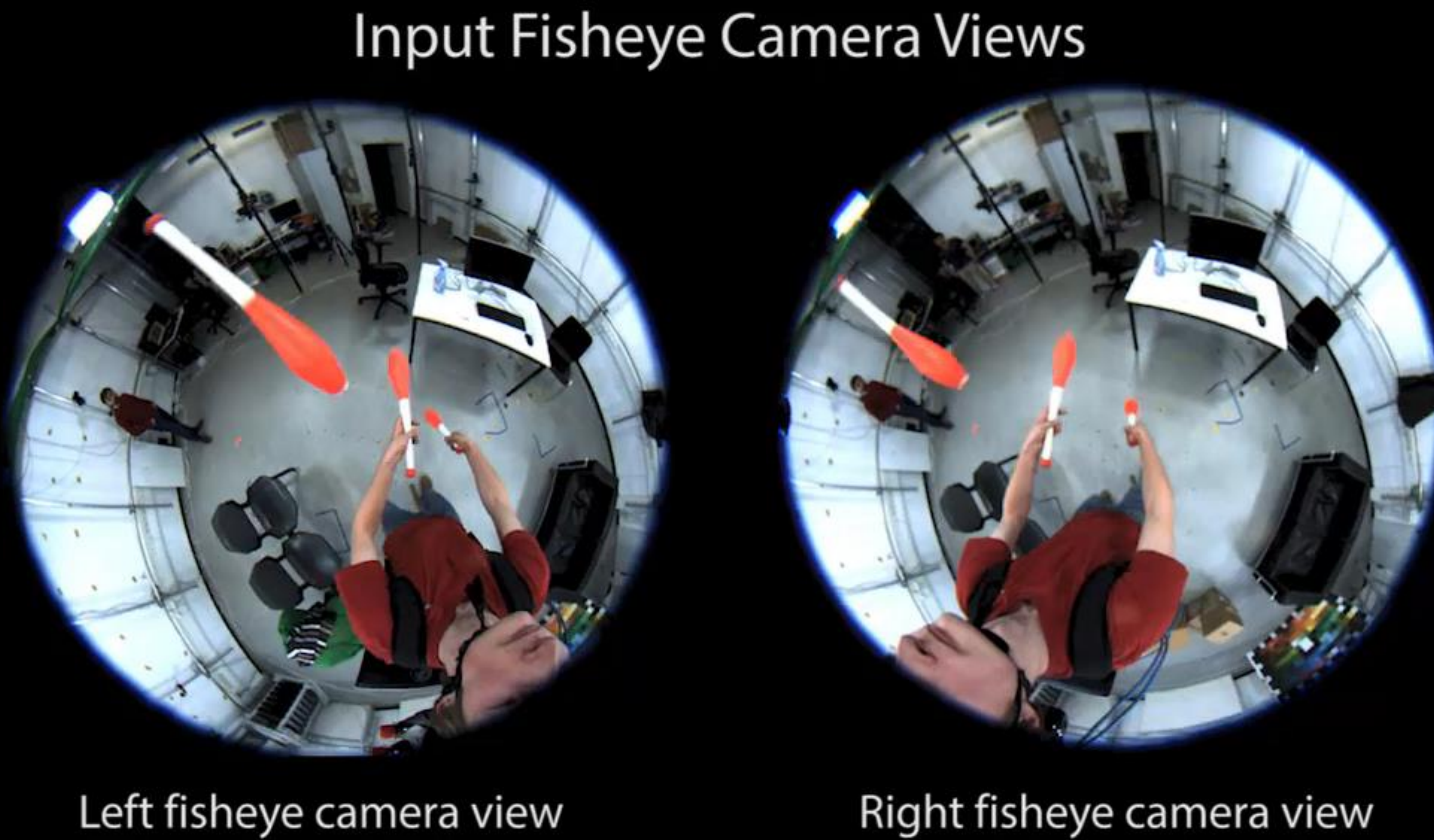
RGB only

Depth ambiguities

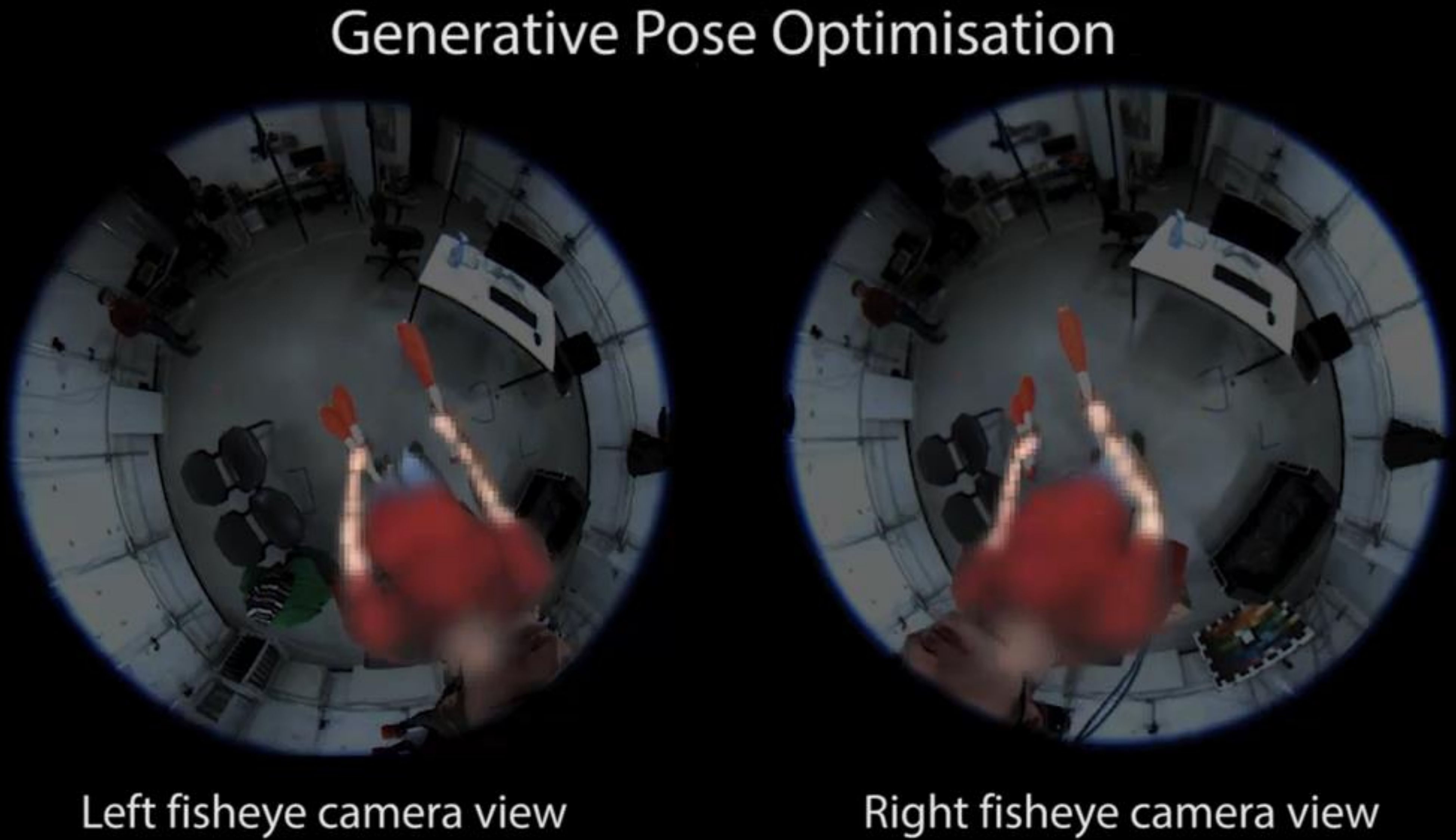
# Model overview



# Method walkthrough



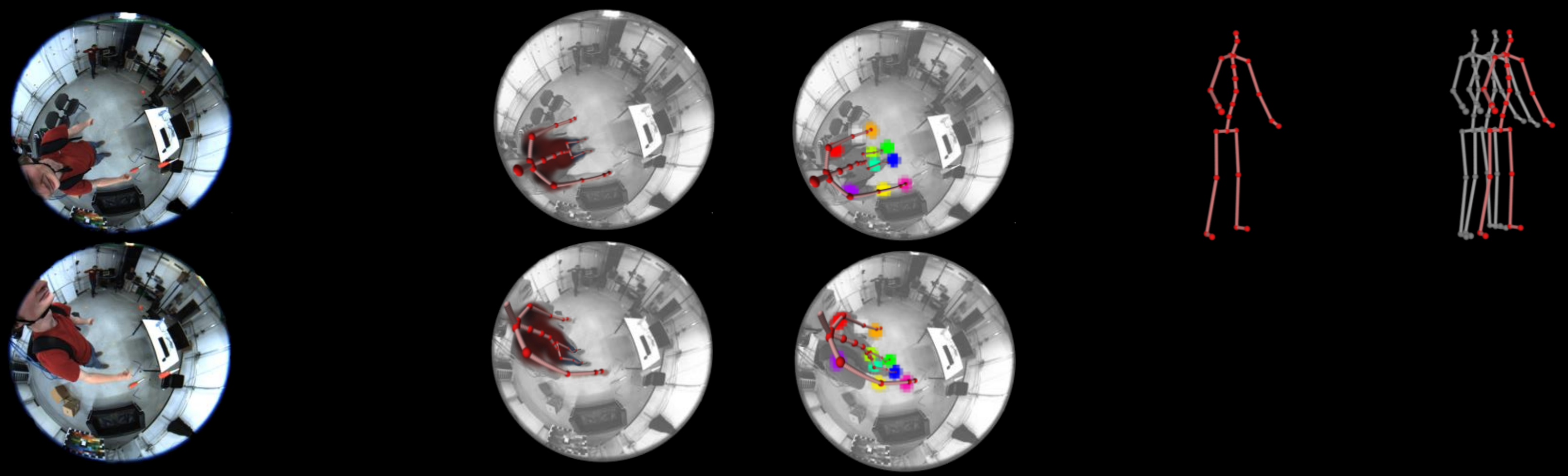
# Method walkthrough



# Combined optimization

- Energy minimization:
  - gradient descent on pose $\mathbf{p}^t$ at time $t$

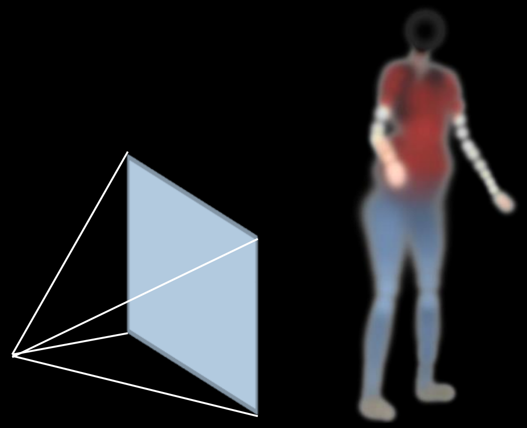
$$E(\mathbf{p}^t) = E_{\text{color}}(\mathbf{p}^t) + E_{\text{detection}}(\mathbf{p}^t) + E_{\text{pose}}(\mathbf{p}^t) + E_{\text{smooth}}(\mathbf{p}^t)$$



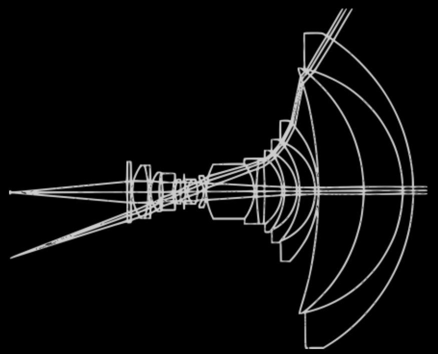
Input Generative Discriminative Prior terms

# Generative model

- Volumetric body model
  - raytracing-based
  - fisheye camera
  - parallel GPU implementation



[Rhodin ICCV 2015, ECCV 2016]



[Scaramuzza 2006]

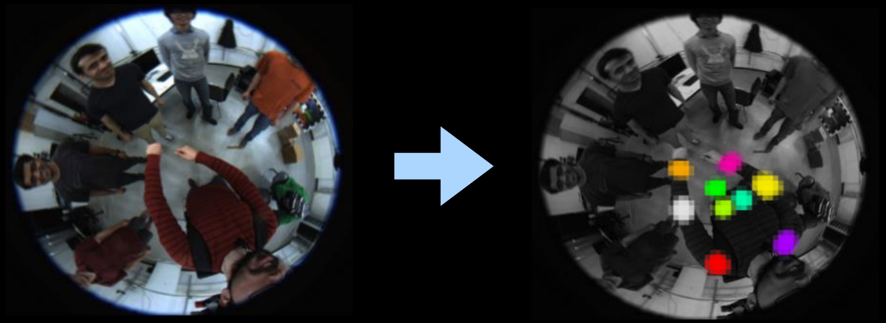
Our model

# Discriminative component

- Deep 2D pose estimation
  - High accuracy with sufficient training data
  - Standard CNN architecture (Residual network [He 2016])

[Insafutdinov 2016, …]

- Egocentric training data?

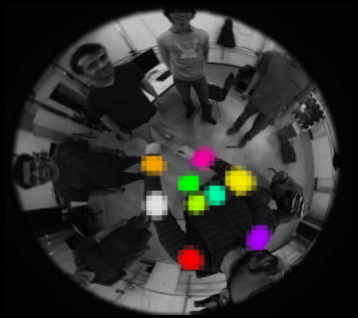


Example image    Annotation

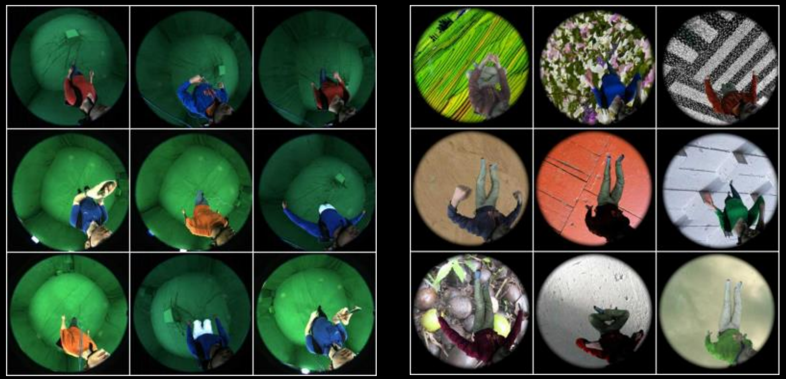
# Training dataset

- Egocentric image-pose database
  - 80,000 images
  - appearance variation
  - background variation
  - actor variation

Example image



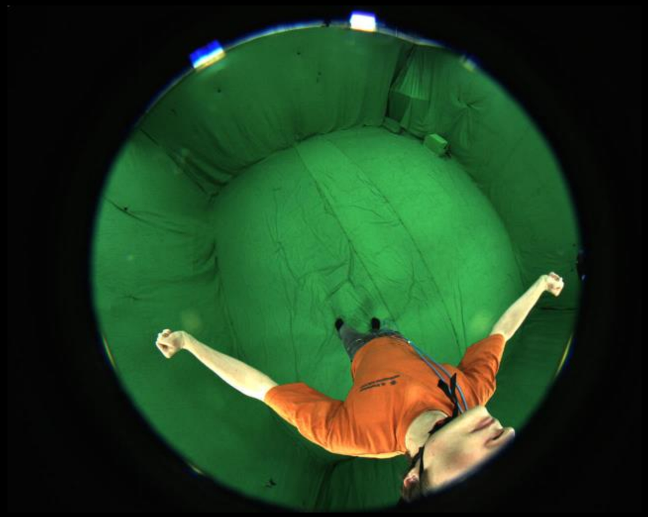
Annotation



Data augmentation

Ground-truth annotation

# Diversity by augmentation: background



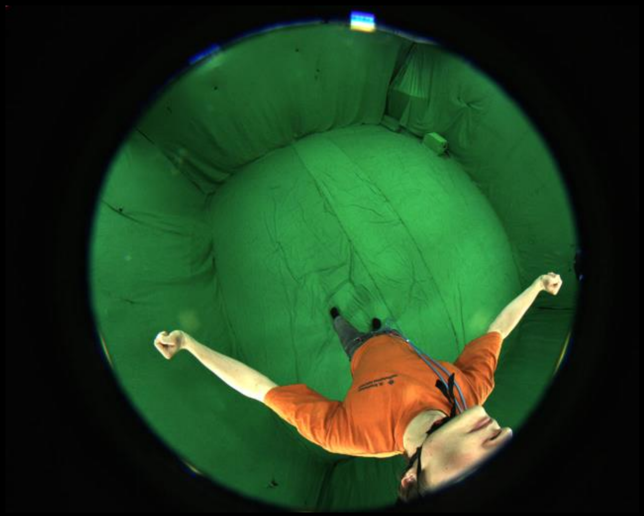
Original

Augmentation

Replaced background

- Green-screen keying to replace backgrounds
  - using random images from Flickr

# Diversity by augmentation: foreground

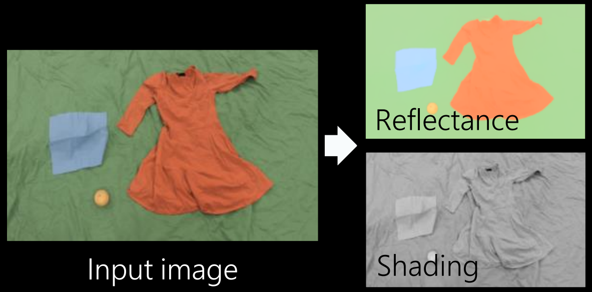


Original

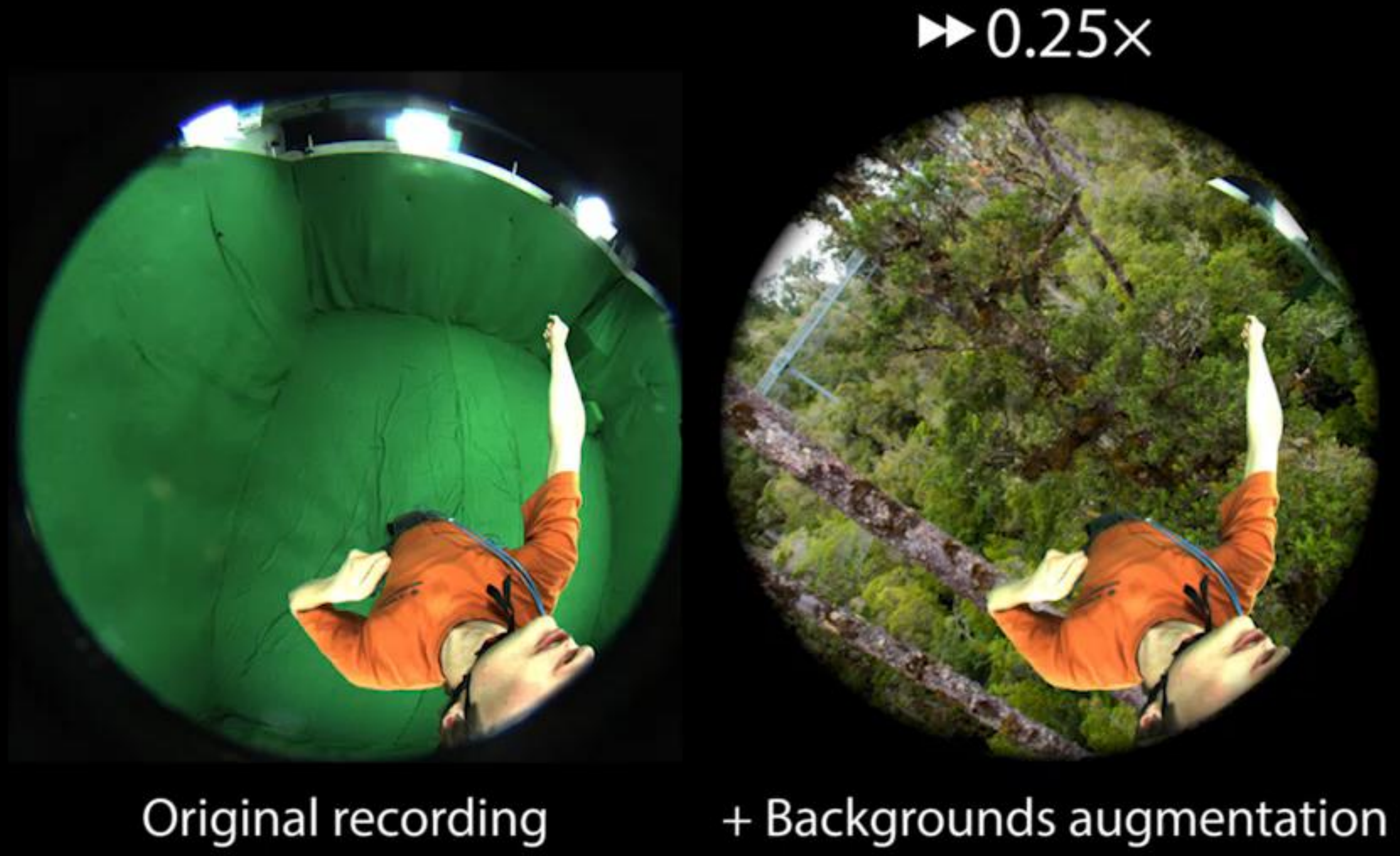
Augmentation

Replaced albedo

- Intrinsic image decomposition [Meka 2016, …]

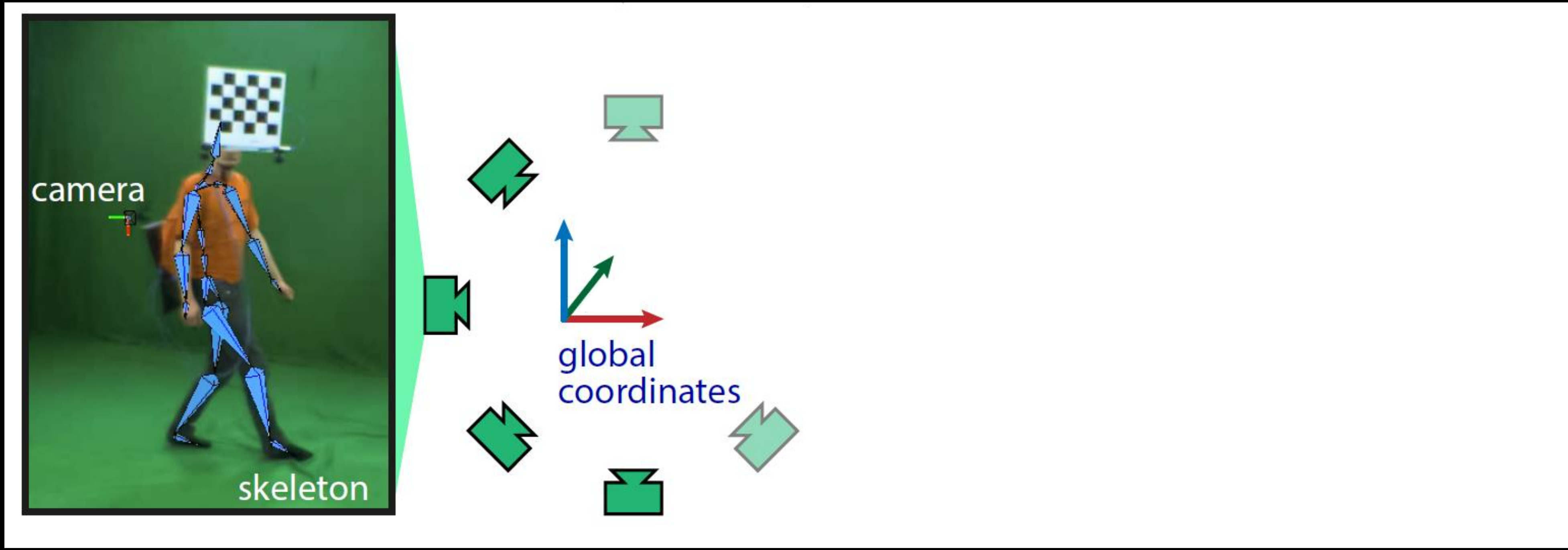


# Training dataset augmentation



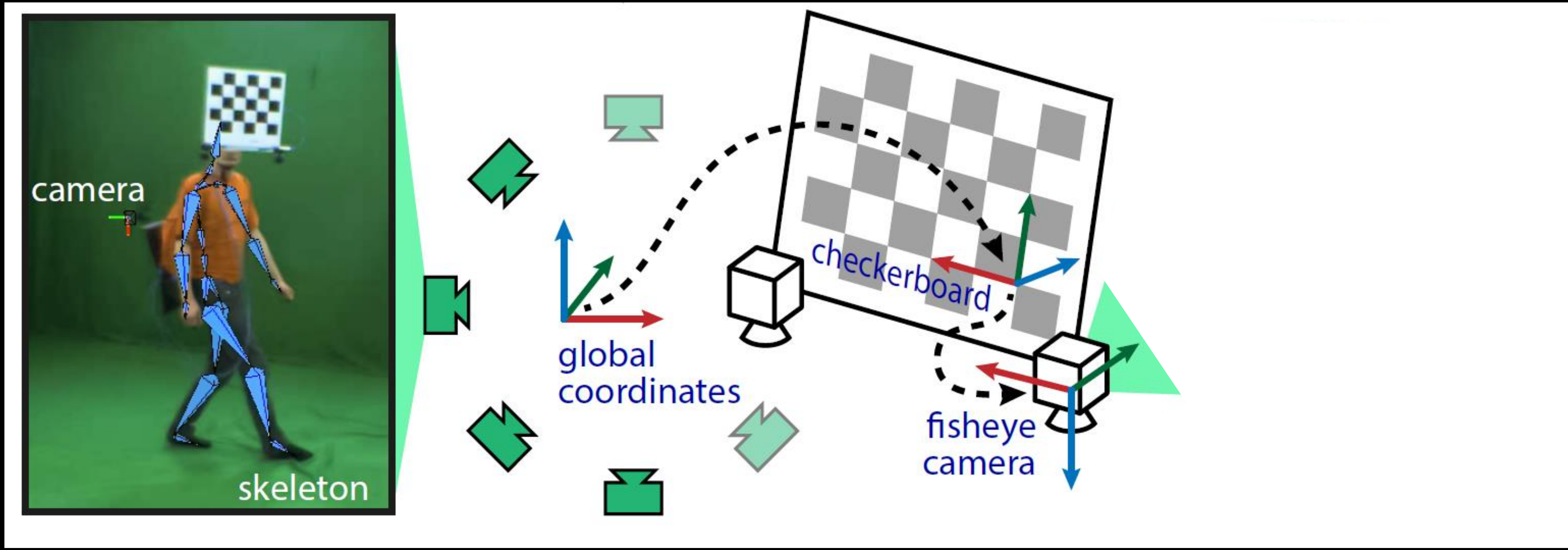
# Automatic ground-truth annotation

Outside-in markerless motion capture



# Automatic ground-truth annotation

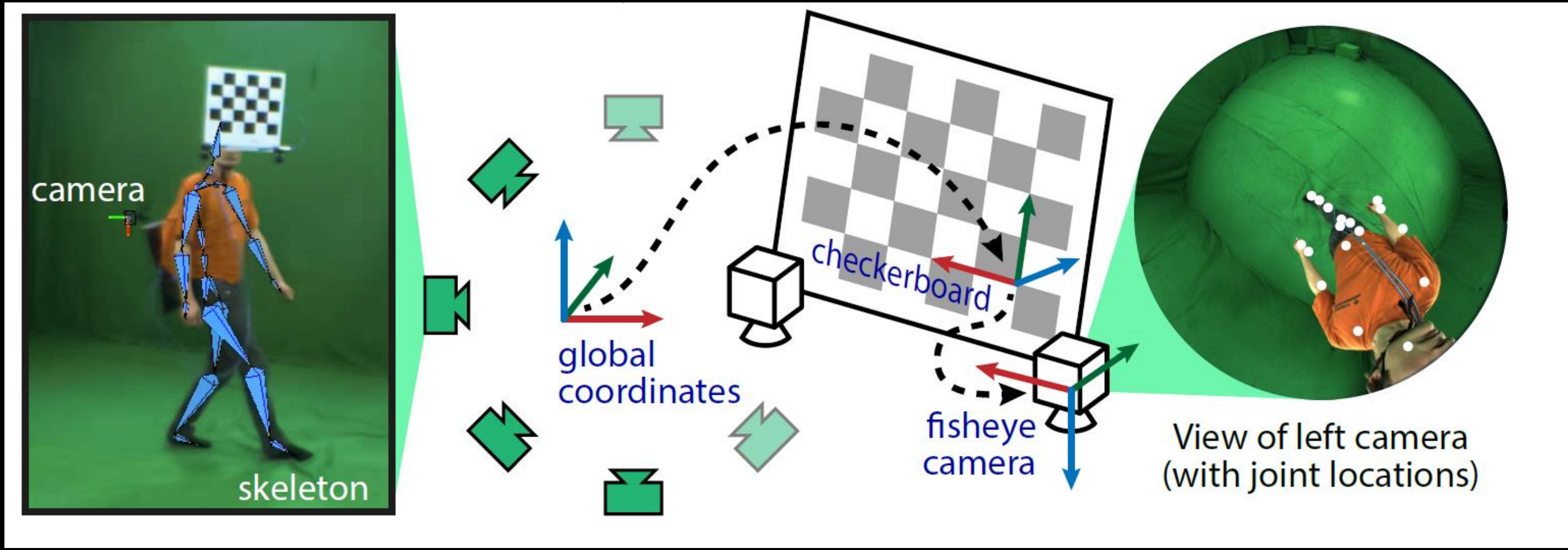
Outside-in markerless motion capture



# Automatic ground-truth annotation

Outside-in markerless motion capture

Projection into dynamic egocentric camera



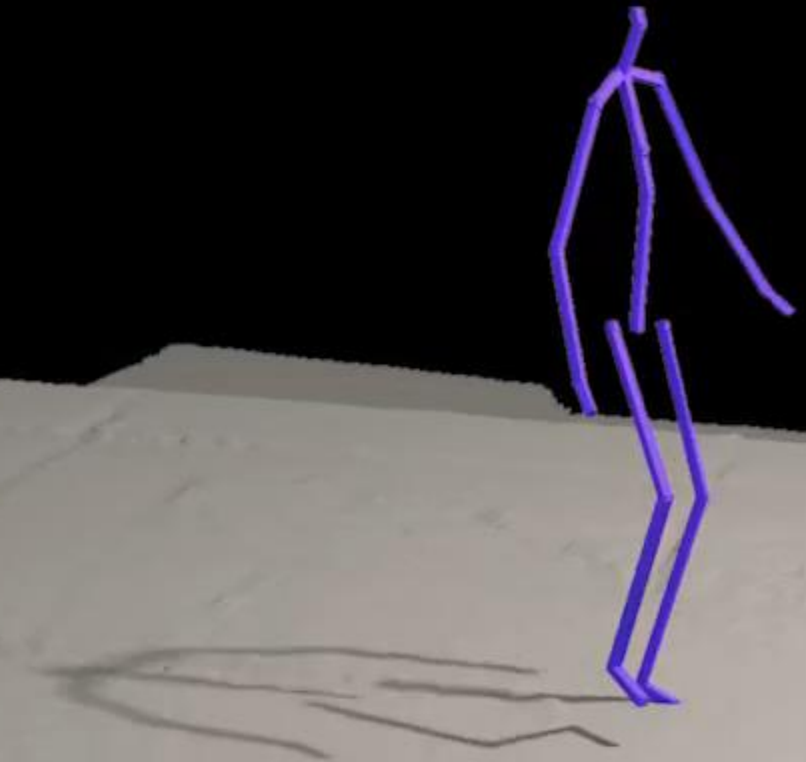
# Constrained and crowded Spaces

Two representative external views – Note the strong occlusions

# Outdoor and large-scale

Left fisheye view

External view
(for reference, not used)



Skeleton combined with
SfM camera pose

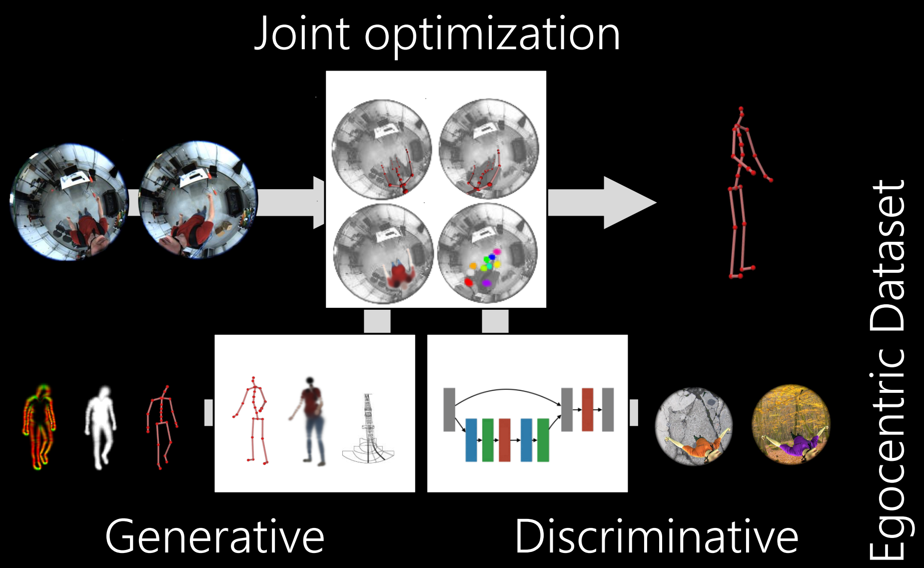
Centered skeleton

# Virtual and augmented reality

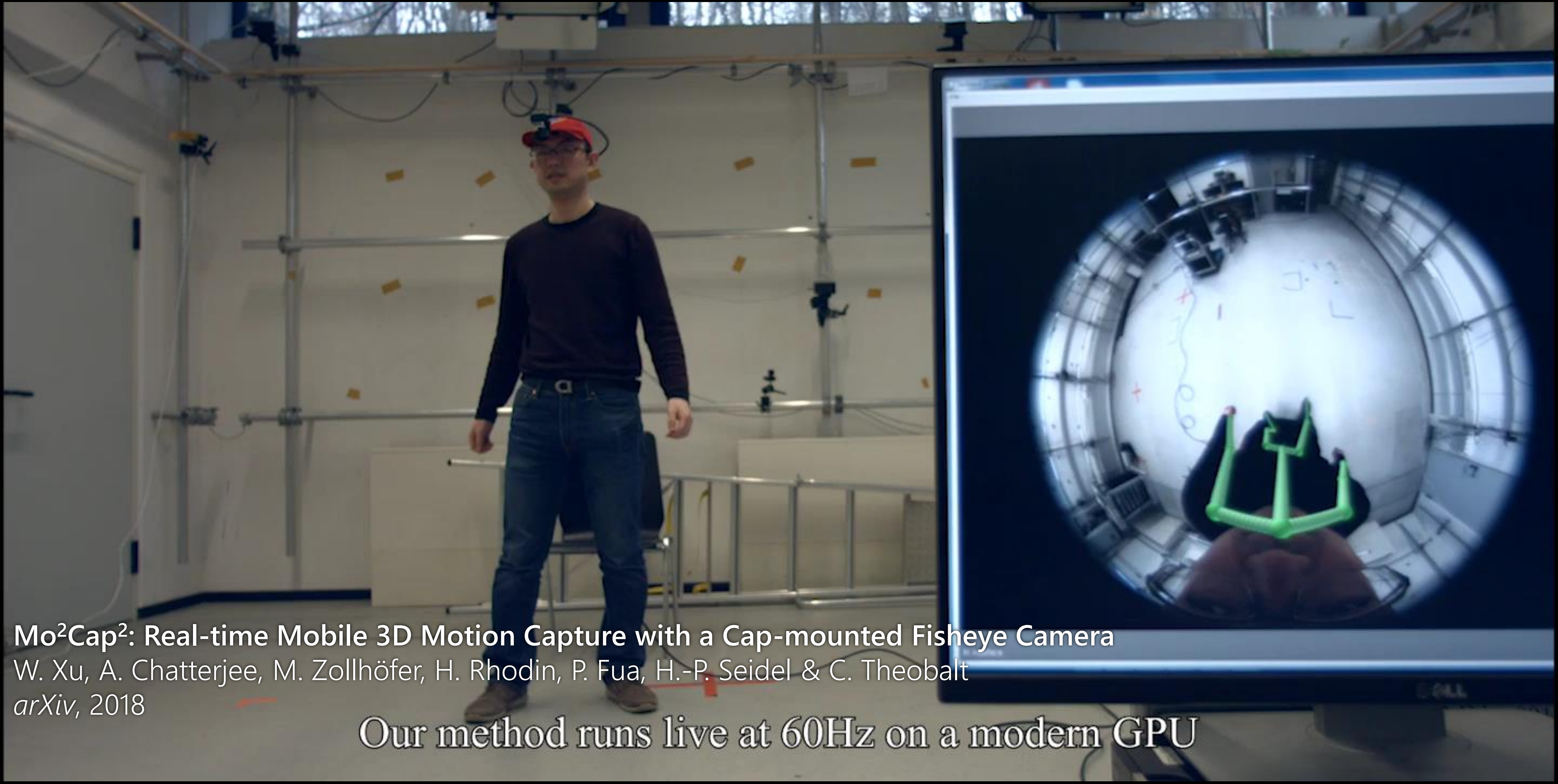
# Embodied virtual reality

# EgoCap summary

- Inside-in motion capture
  - full-body 3D pose
  - easy-to-setup
  - low intrusion level
  - real-time capable
  - general environments
- Future work
  - low latency (for VR)
  - alternative camera placement, monocular
  - capture hands and face



# Single-camera egocentric motion capture




**Mo²Cap²: Real-time Mobile 3D Motion Capture with a Cap-mounted Fisheye Camera**
W. Xu, A. Chatterjee, M. Zollhöfer, H. Rhodin, P. Fua, H.-P. Seidel & C. Theobalt
*arXiv*, 2018

http://gvv.mpi-inf.mpg.de/projects/wxu/Mo2Cap2/

# Quick recap

- Immersion & presence: motion is extremely important
  - presence breaks when visual body motion does not match physical motion
- Tracking in VR/AR: need high accuracy and update rate, low latency
  - in practice, usually best to combine IMUs with optical tracking to fix drift
- Hand input devices: controllers are tracked robustly and accurately
  - hand tracking will soon enable natural interaction with real-world objects
- Full-body motion capture: bring the entire body into VR
  - marker-based systems are fast, robust, accurate and very expensive
  - markerless systems allow live motion capture from just 1 or 2 cameras

# Questions?

Christian Richardt

## Motion-Aware Displays

SIGGRAPH Asia Course on Cutting-Edge VR/AR Display Technologies

SIGGRAPH ASIA 2018 TOKYO

CAMERA
Centre for the Analysis of Motion, Entertainment Research and Applications

UNIVERSITY OF BATH

richardt.name
c_richardt