

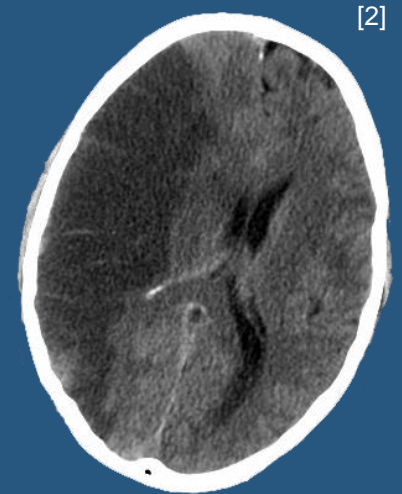
Benjamin Busam, Marco Esposito,  
Simon Che'Rose, Nassir Navab, Benjamin Frisch

# A Stereo Vision Approach for Cooperative Robotic Movement Therapy

# Medical Motivation

## Movement Therapy after Stroke

- Poor blood flow in brain
  - Cell damage
  - ~17 Mio incidents p.a.
  - 33 Mio affected patients
  - 80% hemiparesis
- Rehabilitation therapy



[1] K. A. Leber. Neurochirurgie Graz. 2015-11-12

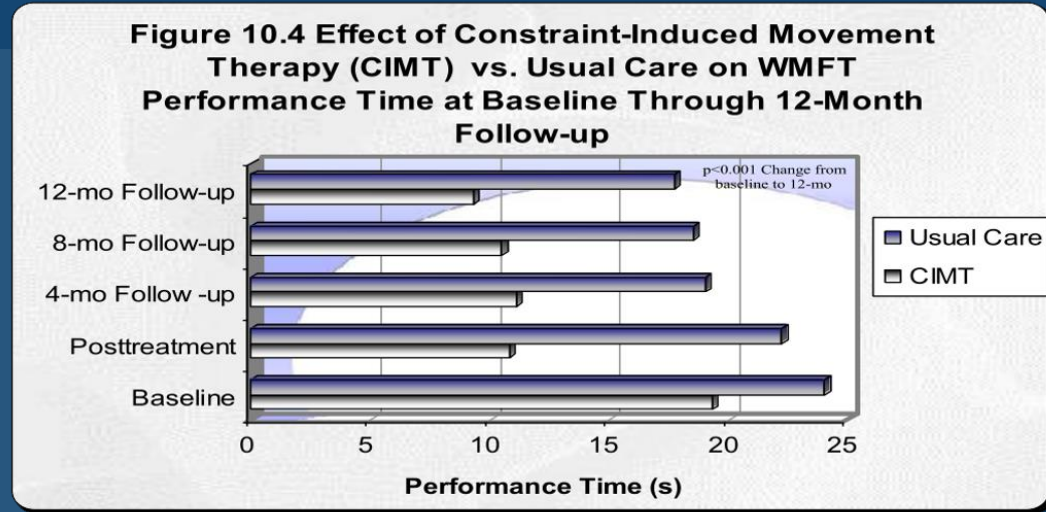
[2] L. Monfils. Dutch Radiology. 2008

# Movement Therapy after Stroke

## Therapeutic Measures

- Neurological therapeutics
- Constraint-induced movement
- **Mirror therapy**
- Repetitive practice
- Re-education of movements
  - Motion training
  - Immediate & long term

➤ Patient participation very important [2]



[1]

[1] N. Foley et al. EBRSR. 2013

[2] A. A. Blank et al. Current Physical medicine and rehabilitation reports. 2014

# Assistive Movement Therapy

## Motion Training

- Previous Systems
  - Joystick controlled
  - Exoskeletons
- Our Approach
  - Contactless with computer vision
  - Optical tracking controlled
  - Collaborative robot movement therapy



Bi-Manu Track

[2]



T-WREX Exoskeleton

[1]

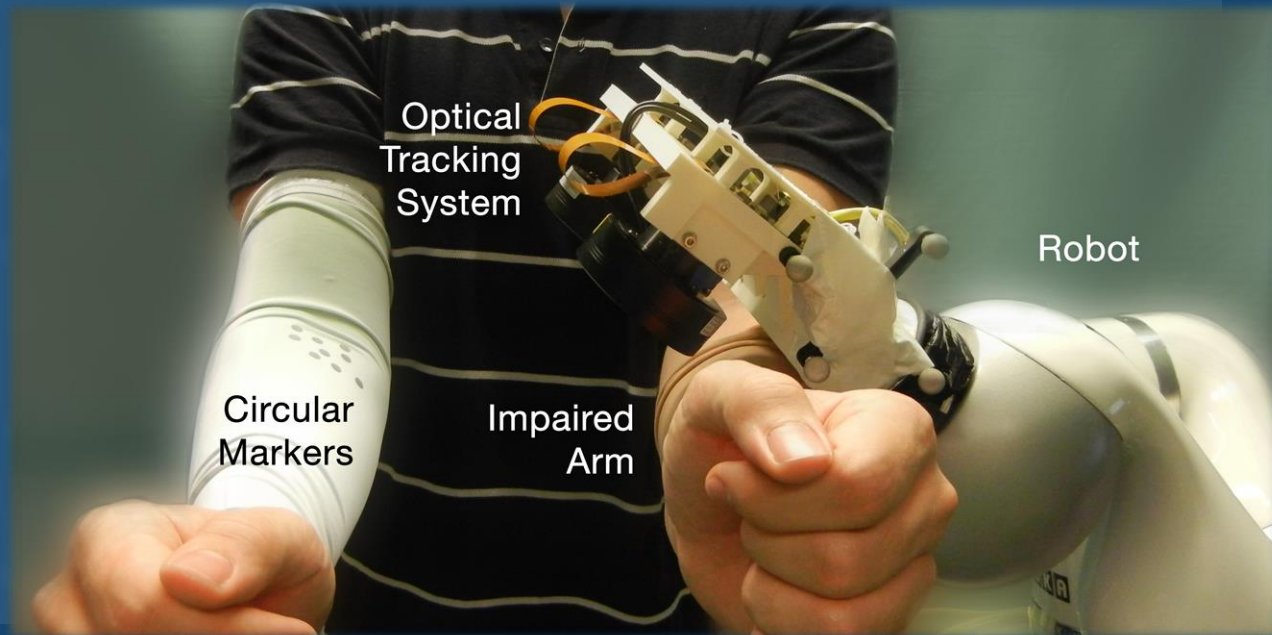
[1] L. Marchal-Crespo et al. JNER. 2009

[2] Reha-Stim. Bi-Manu-Track. 2015-11-12

# Assistive Movement Therapy

## Proposed Treatment

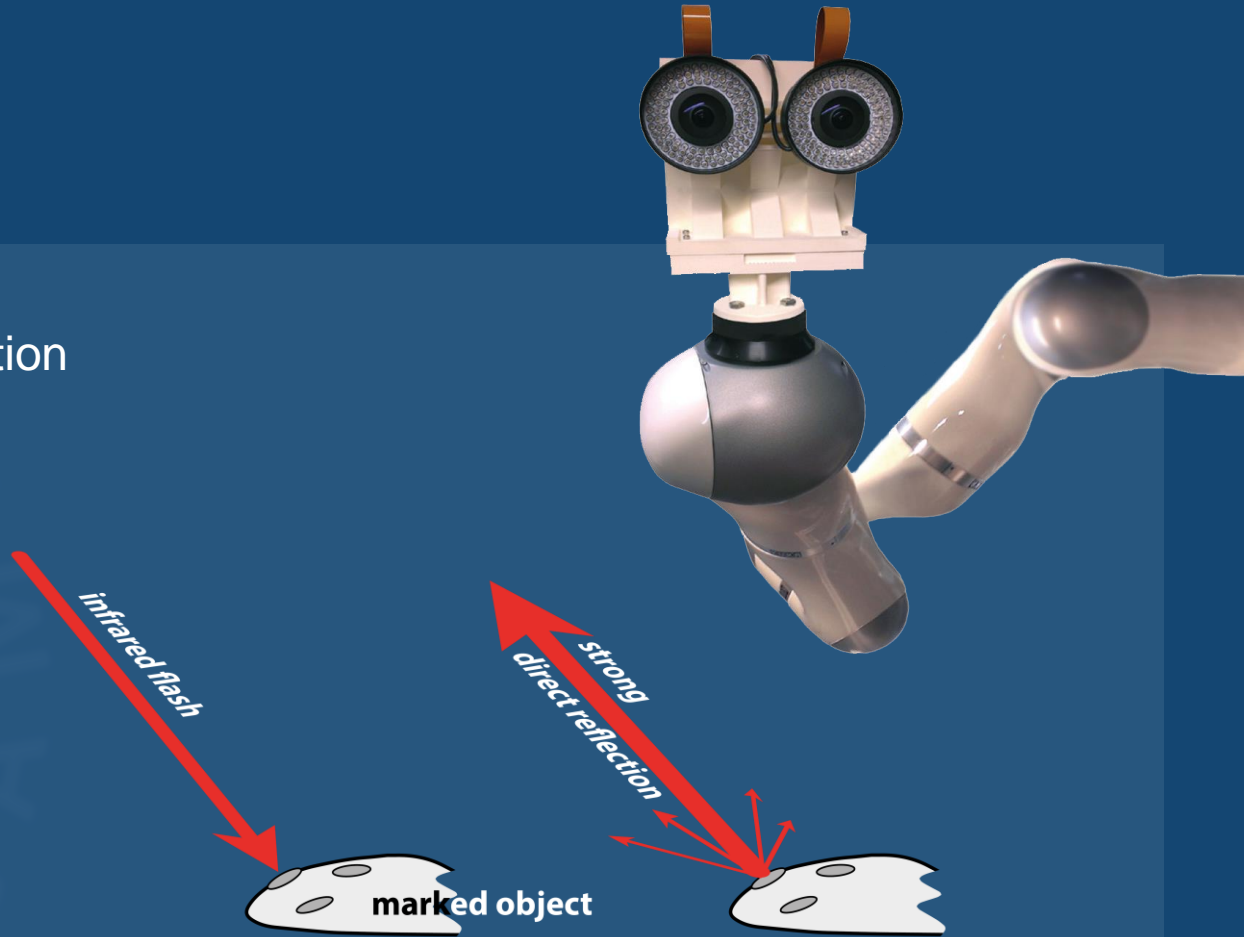
- Camera-in-hand
- Sleeve markers
- Guiding arm
- Robot supports deficient arm
- Robot follows
- Intuitive control of robot movement



# Hardware

## Vision & Robotics

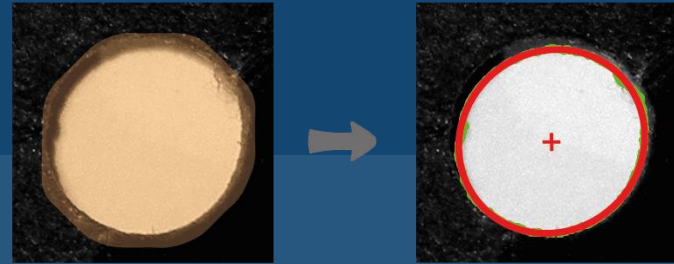
- Stereo camera setup
  - Direct LED ring illumination
  - Infrared filters
  - Passive markers
    - Self-adhesive
    - Retro reflective
  - Light-weight robotic arm
- Inside-out Tracking



# Image Processing

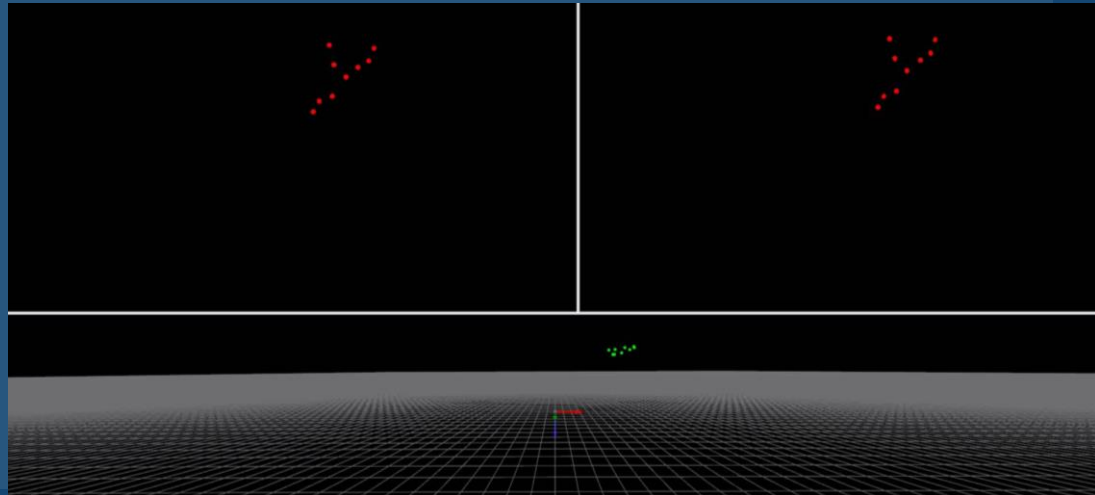
## 2D/3D Object Recognition

1. Acquire images
2. Find object markers (ROIs) [1]
3. Subpixel precise contour fitting [2]
4. Compute centres
5. Triangulate 3D points

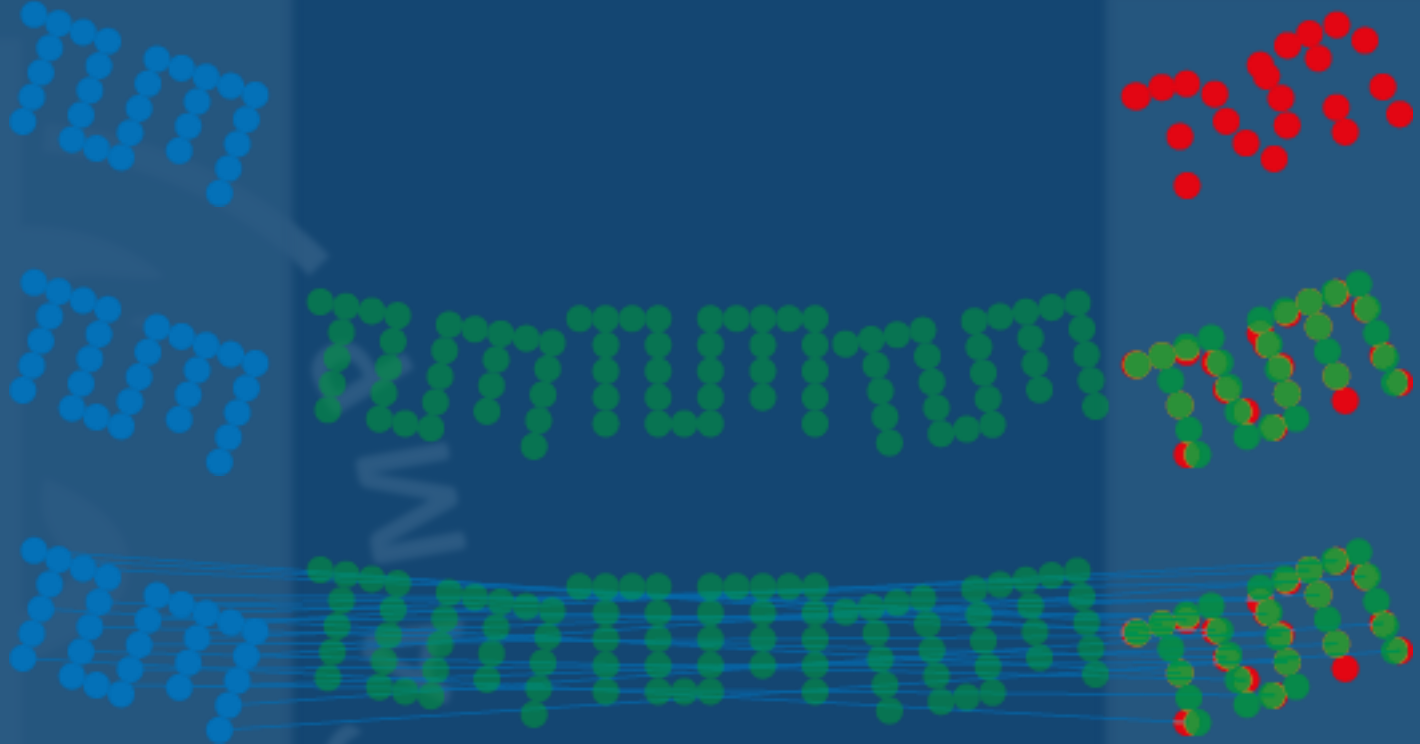


[1] Lindeberg. CVPR 1996

[2] O'Leary, Zsombor-Murray. JEI. 2004



# Sparse Point Cloud Registration



$$X = \{\mathbf{x}_j \in \mathbb{R}^3 \mid 1 \leq j \leq J\}$$

$$Y = \{\mathbf{y}_k \in \mathbb{R}^3 \mid 1 \leq k \leq K\}$$



# Tracking Algorithm

## 3D Pose Estimation

- Arbitrary motion = 6 DOFs
- Minimize energy functional
  - Individual marker set-up
  - Robust recognition

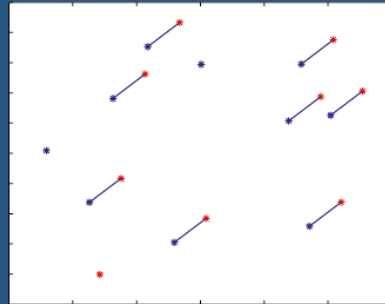
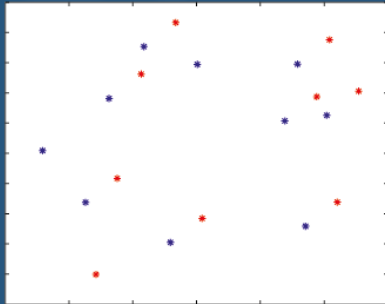
$$E(\mathbf{M}, \mathbf{R}, \mathbf{t}) = \sum_{j=1}^J \sum_{k=1}^K m_{jk} \|\mathbf{y}_k - (\mathbf{R}\mathbf{x}_j + \mathbf{t})\|^2 - \alpha \sum_{j=1}^J \sum_{k=1}^K m_{jk}$$

Constraints

$$\sum_k m_{jk} \leq 1 \quad \forall j \in \{1, 2, \dots, J\}$$

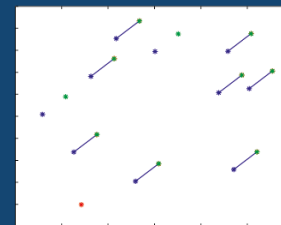
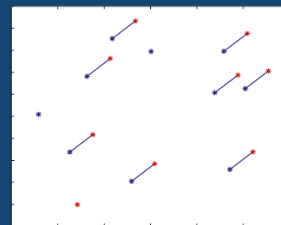
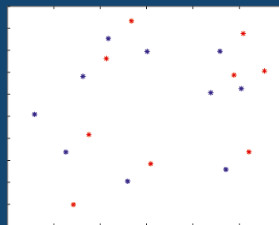
$$\sum_j m_{jk} \leq 1 \quad \forall k \in \{1, 2, \dots, K\}$$

$$m_{jk} \in \{0, 1\} \quad \forall j \in \{1, 2, \dots, J\}, k \in \{1, 2, \dots, K\}$$



$$m_{jk} = \begin{cases} 1, & \text{if } \mathbf{x}_j \leftrightarrow \mathbf{y}_k \\ 0, & \text{otherwise} \end{cases}$$

# Tracking Algorithm



## 3D Pose Estimation

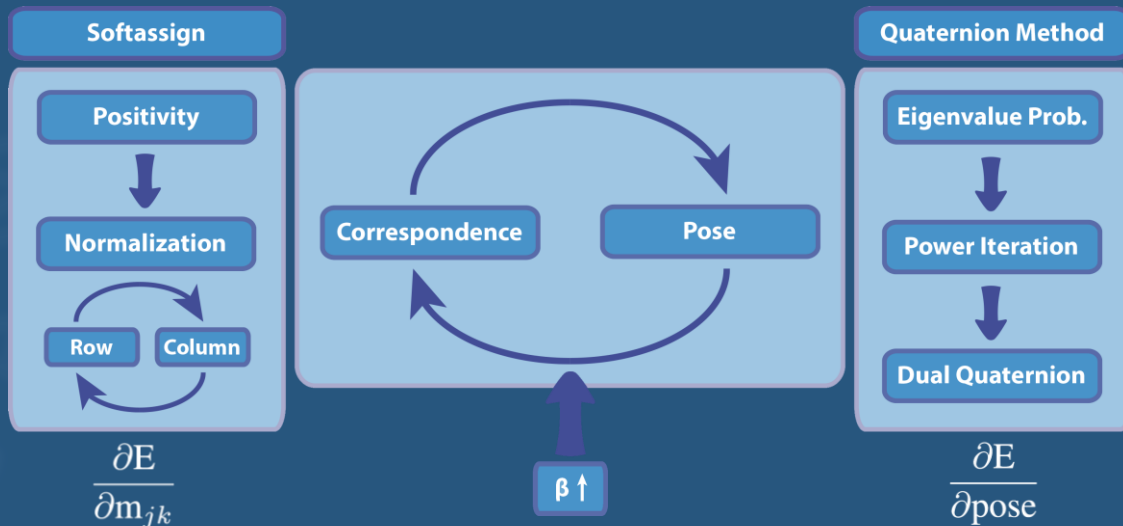
- Arbitrary motion = 6 DOFs
- Minimize energy functional
  - Individual marker set-up
  - Robust recognition
  - Real-time tracking
  - Online teaching

$$E(\mathbf{M}, \mathbf{R}, \mathbf{t}) = \sum_{j=1}^J \sum_{k=1}^K m_{jk} \|\mathbf{y}_k - (\mathbf{R}\mathbf{x}_j + \mathbf{t})\|^2 - \alpha \sum_{j=1}^J \sum_{k=1}^K m_{jk}$$

➤ Mutual approximation in each frame pair

$$\bar{\mathbf{M}}(\beta) \xrightarrow{\beta \rightarrow \infty} \mathbf{M}$$

$$\frac{\partial E}{\partial m_{jk}}$$



# Processing Pipeline

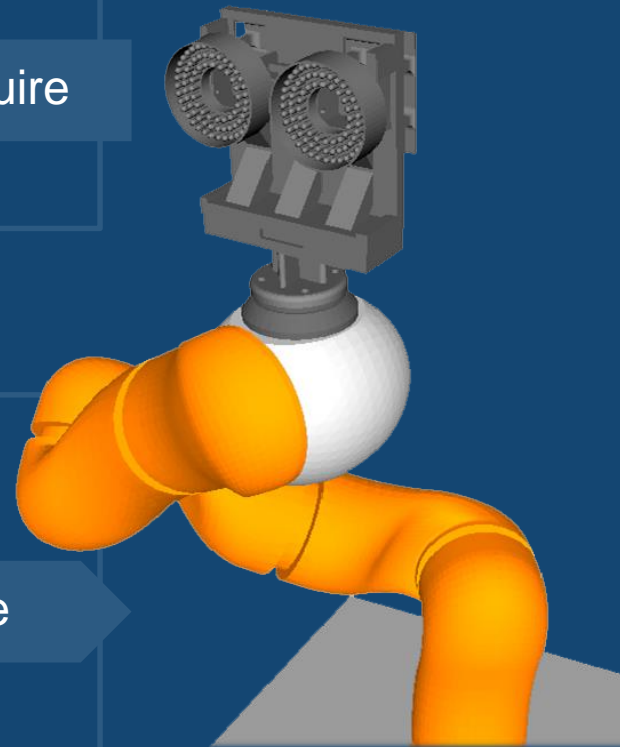
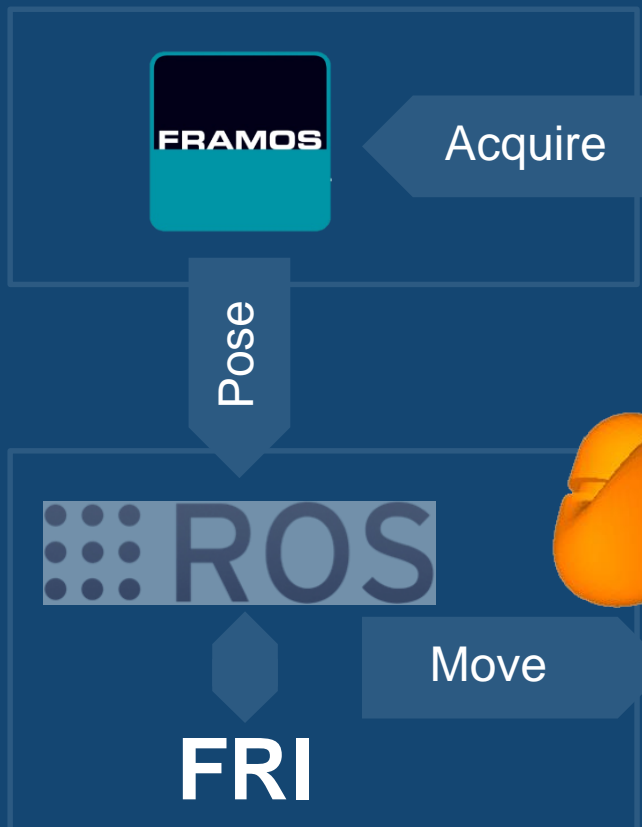
## Involved Parts

- Calibration
  - Camera Intrinsics + Stereo
  - Hand-eye calibration [1]
- Communication
  - OpenIGTLink [2]
- Robot Path Planning
  - RRT-connect [3]

[1] Tsai, Lenz. TRA. 1989

[2] Tokuda et al. MRCAS 2009

[3] Kuffner. ICRA 2000



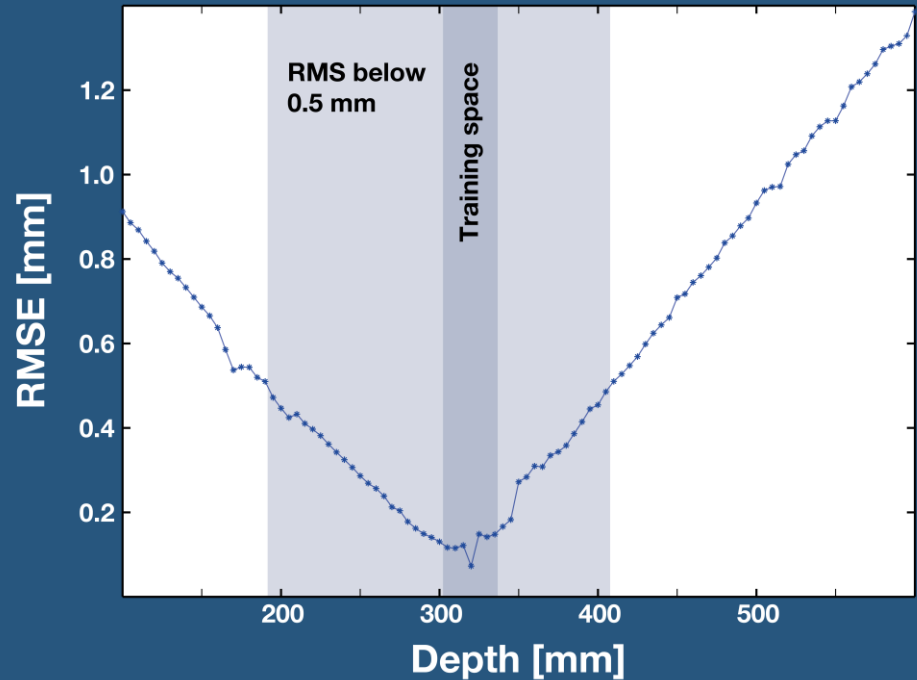
# Experiment 1

## System Validation

# Quantitative Validation

## Accuracy and Robustness

- Accuracy in working volume
  - Move robot in  $60 \times 60 \times 40 \text{ mm}^3$
  - Total translation error 0.5 mm
- Tracking error
  - Move target to different distances
- Partial occlusion
  - Qualitative experiments
  - Tracking with up to 50% occlusion



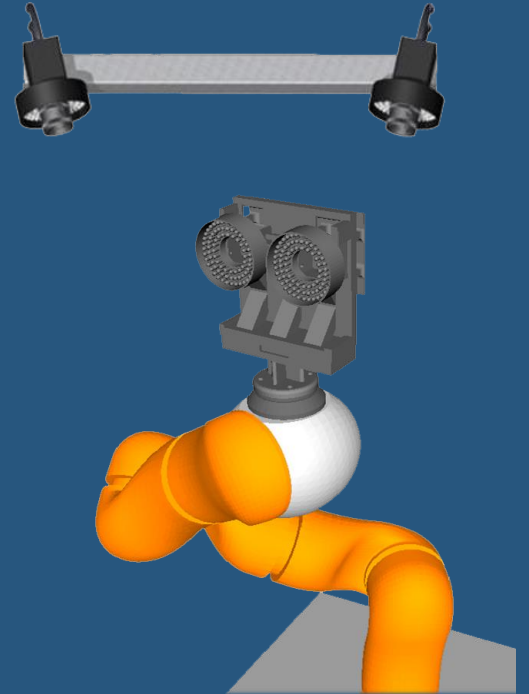
# Experiment 2

## Latency Tests

# Conclusion and Discussion

## Results and Outlook

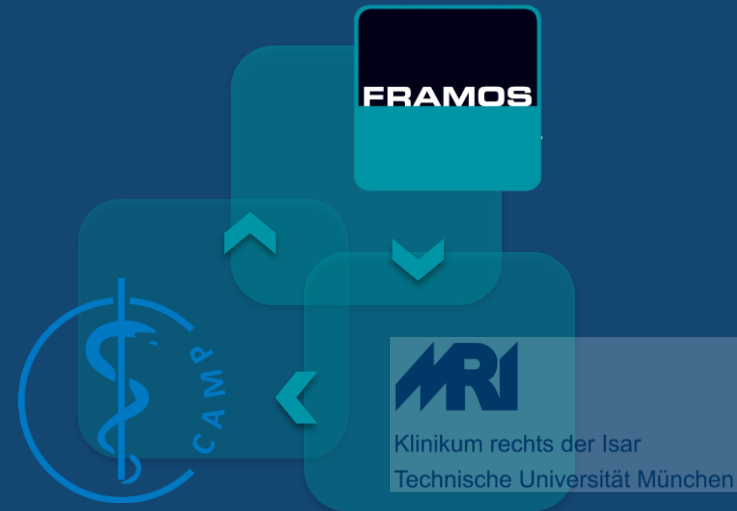
- Camera-in-hand tracking solution
  - Generic marker-based algorithm
  - Robust and real-time
- Collaborative robotics for rehabilitation
  - First concept demonstrator using inside-out tracking
  - Very simple movements
- Feasibility and evaluation
  - Tests with healthy individuals
  - Intuitive control mechanism



# THANK YOU!

Vielen Dank!

## Questions ?





# Backup

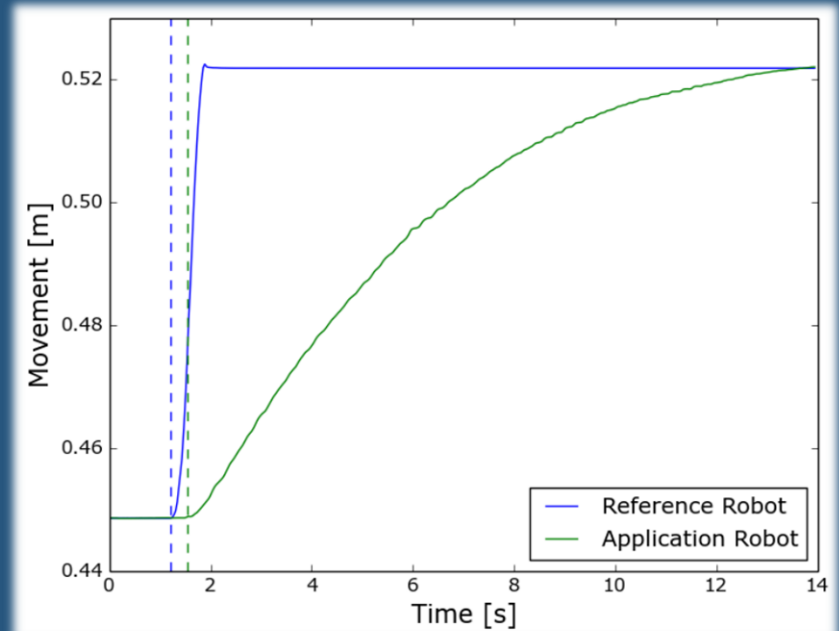
## Software Parts and Libraries

- Vision
  - FRAMOS Application Framework (FRAMOS Imaging Systems, Germany)
- Robot
  - Control: Fast Research Interface (KUKA, Germany) and ROS framework
  - Pose monitoring: TF library
  - Path planning and self-collision avoidance: MoveIt!, OMPL, RRT-Connect
- Calibration
  - Camera calibration: MATLAB Calibration Toolbox
  - Hand-eye calibration: ViSP library (Tsai-Lenz algorithm)
- Communication
  - TCP/IP: OpenIGTLink API

# Backup

## Latency Tests

- 1<sup>st</sup> light-weight robot
  - Observes movement of target
- 2<sup>nd</sup> light-weight robot
  - Holds target: 10 markers
- Outside-in tracking system
  - Co-calibration
  - Observe movement



# Backup

$$E(\mathbf{M}, \mathbf{R}, \mathbf{t}) = \sum_{j=1}^J \sum_{k=1}^K m_{jk} \|\mathbf{y}_k - (\mathbf{R}\mathbf{x}_j + \mathbf{t})\|^2 - \alpha \sum_{j=1}^J \sum_{k=1}^K m_{jk}$$

## Parameter Initialization and Updates

- Initialize

- $\mathbf{M}, \mathbf{R}, \mathbf{t}$

- $\mathbf{R}_0 = \mathbb{1}$ ,  $\mathbf{t}_0$  centre of mass
    - $\mathbf{R}_0, \mathbf{t}_0$  from previous frame
    - $(\mathbf{M}_0)_{jk} = 1 + \varepsilon$

- Parameters

- $\beta_0 = 10^{-4}$
    - $\beta_{inc} = 1.053$
    - $\beta_{max} = 10^3$

- Confidence loop:  $\beta = \beta\beta_{inc}$

- Convergence loop for  $\mathbf{R}, \mathbf{t}$

- Softassign: Update  $\mathbf{M}$ 
      - Partial derivatives and positivity
      - 2D Normalization [1]
    - Pose update:  $\mathbf{R}, \mathbf{t}$ 
      - Dual quaternion pair

[1] Sinkhorn. Annals of Mathematical Statistics. 1964

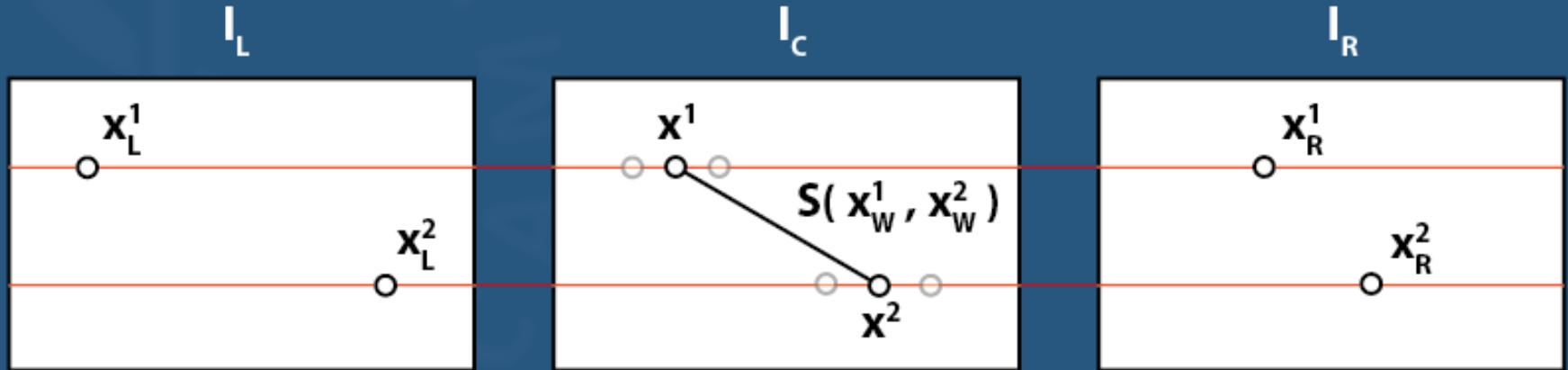
# Backup

## Stereo Triangulation

- Disparity gradient

$$\Gamma(\mathbf{x}_W^1, \mathbf{x}_W^2) = \frac{D(\mathbf{x}_W^1, \mathbf{x}_W^2)}{S(\mathbf{x}_W^1, \mathbf{x}_W^2)} \in [-1, 1]$$

$$\mathbf{x}_C^i = \left( \frac{x_{Lx}^i + x_{Rx}^i}{2}, x_y^i \right), \quad i \in \{1, 2\}$$



# Backup

## Material and Hardware

- **Robots**
  - Light-weight robotic arm: LBR 4+ (KUKA, Germany)
  - Latency tests: UR-6-85-5-A (Universal Robots, Denmark)
- **Vision System**
  - Cameras: GC1291M-BL (SMARTEK Vision, Croatia)
  - Lenses: Fisheye 135° FoV. DSL315B-NIR (Sunex, USA)
  - Filters: IF 093 NIR bandpass (Schneider-Kreuznach, Germany)
  - Illumination: Direct ringlight FLDR-i70A @ 875 nm (FALCON Illumination, Malaysia)
  - Strobe controller: IPSC2 (SMARTEK Vision, Croatia)
  - External tracking system: Polaris Vicra (NDI, Canada)
- **Computing Hardware**
  - Image processing & tracking: Intel Core i7 960 @ 3.2 GHz
  - Robot control: Intel Core i5 4690K @ 3.5 GHz
- **Markers: Retroreflective film (3M, USA)**