Encountered-type haptic interface for virtual interaction with real objects based on implicit surface haptic rendering for remote palpation

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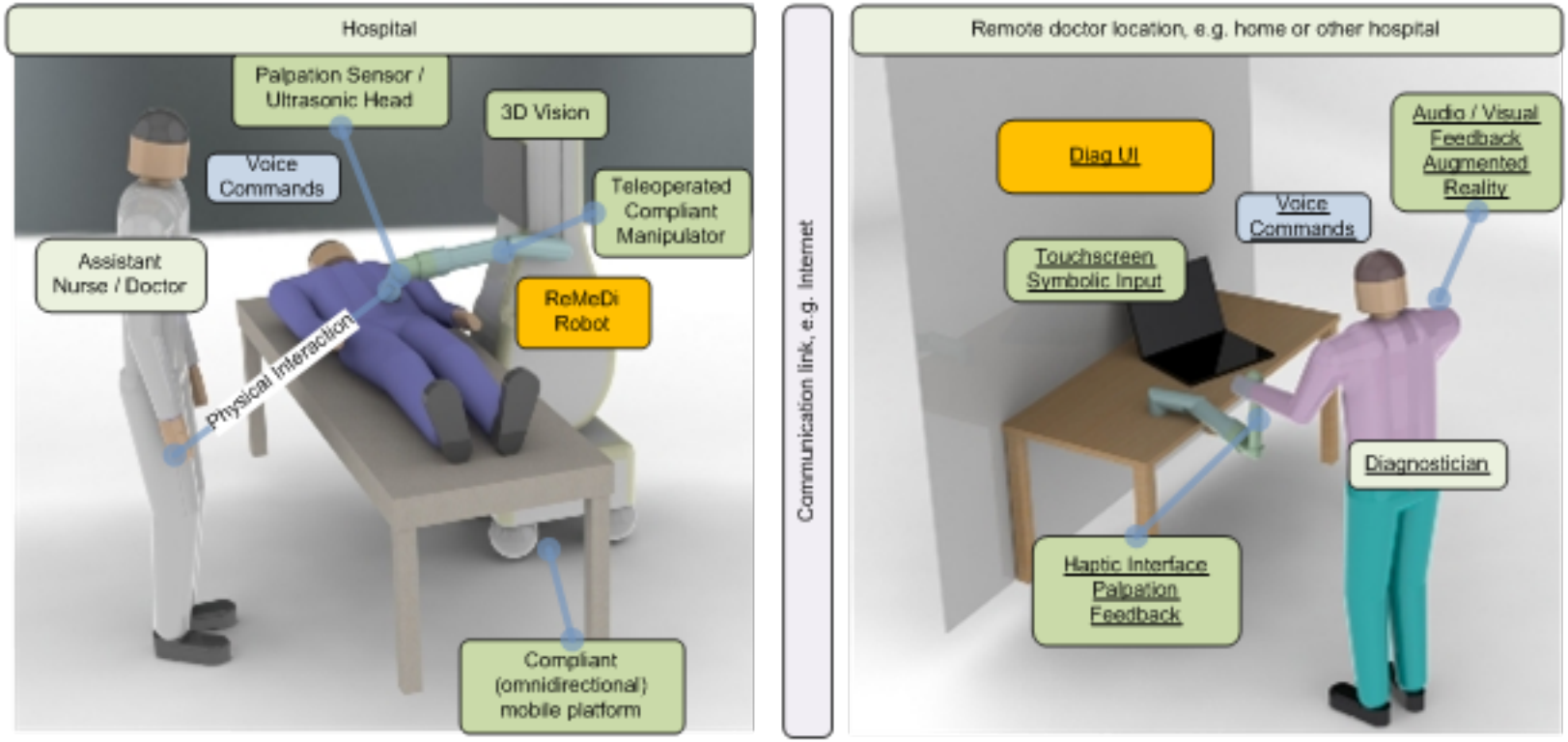
Tele-Palpation in EU-Funded ReMeDi FP7

Why tele-palpation?

- The shortage of physicians in developed countries encourages engineers and doctors to collaborate towards the development of telemedicine.



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Design Objectives

Objectives based on Doctors' interviews

- Allows the doctors to move freely their hands in the space when they are out of the patient's body
- Receive a force feedback only when they interact with the patient
- Visual feedback from the patient site

Design Solutions

Haptic feedback

- Encountered haptic [1]:
  - User in contact with the robot end-effector only when in contact with the virtual object.
  - It can work also with dynamic objects
- Hand tracking system required
- Real-time haptic renderer from remote point-cloud

Visual feedback

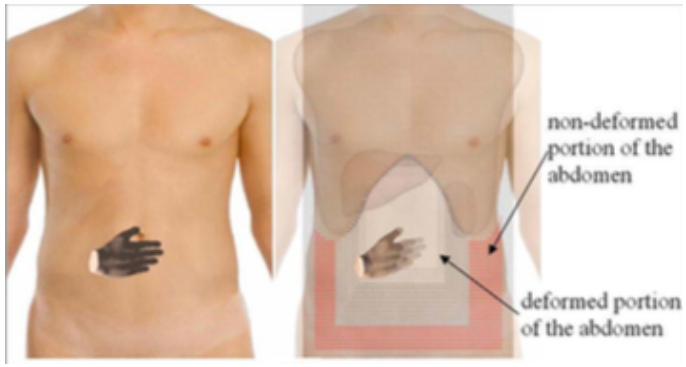
- 3D Scene visualization
- Augmented Reality approach

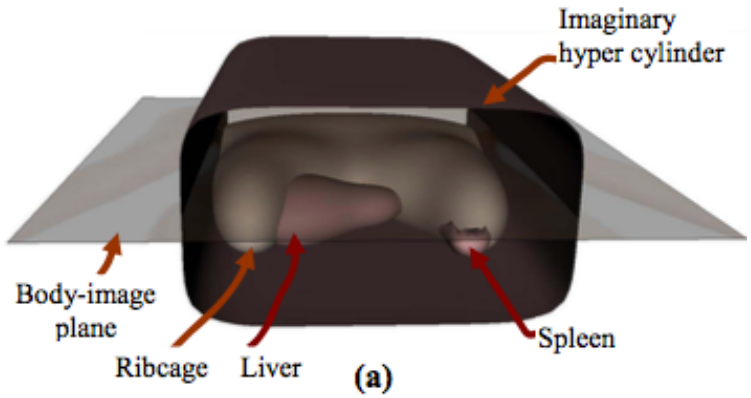
[1] Ruffaldi et a l. “Haptic rendering of juggling with encountered type interfaces” (2011)

Virtual Palpation Solutions

- Coles et al. “PalpSim” (2011) – full system

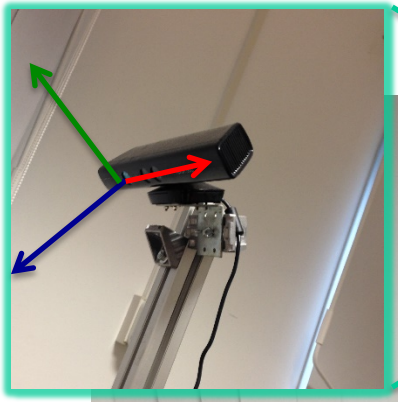
- Yasmin and Sourin (2012) – haptic rendering on virtual body





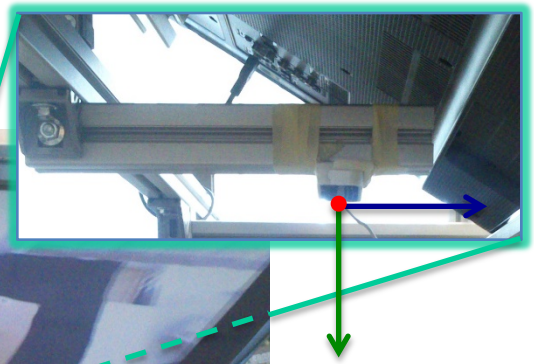
System Setup

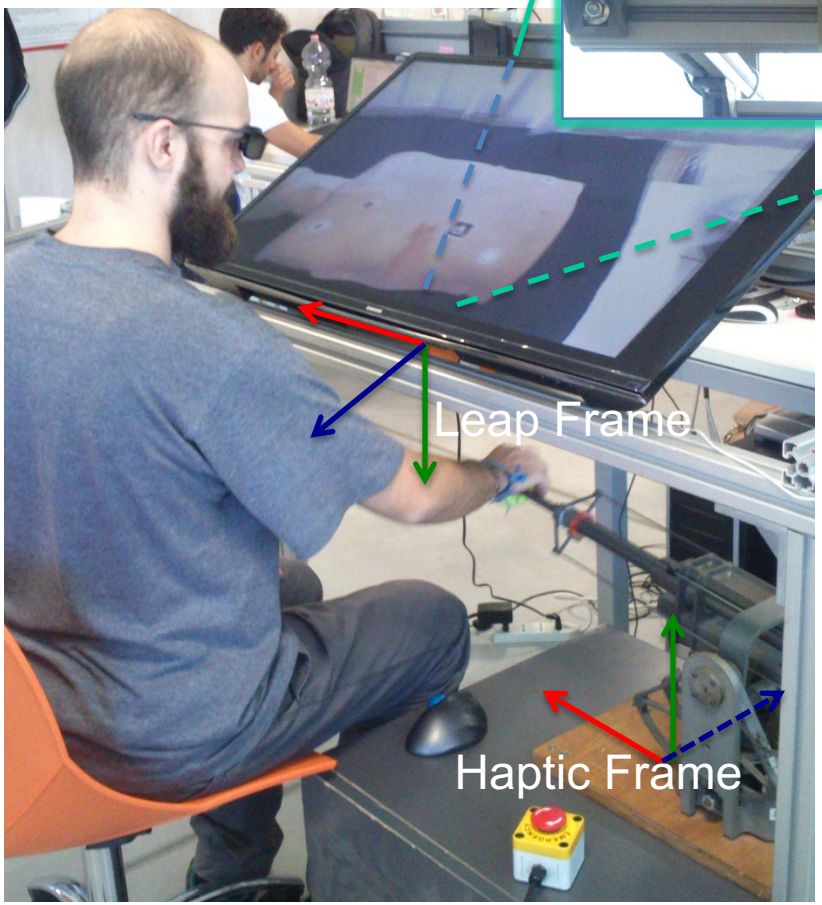
Kinect Frame



Patient Site

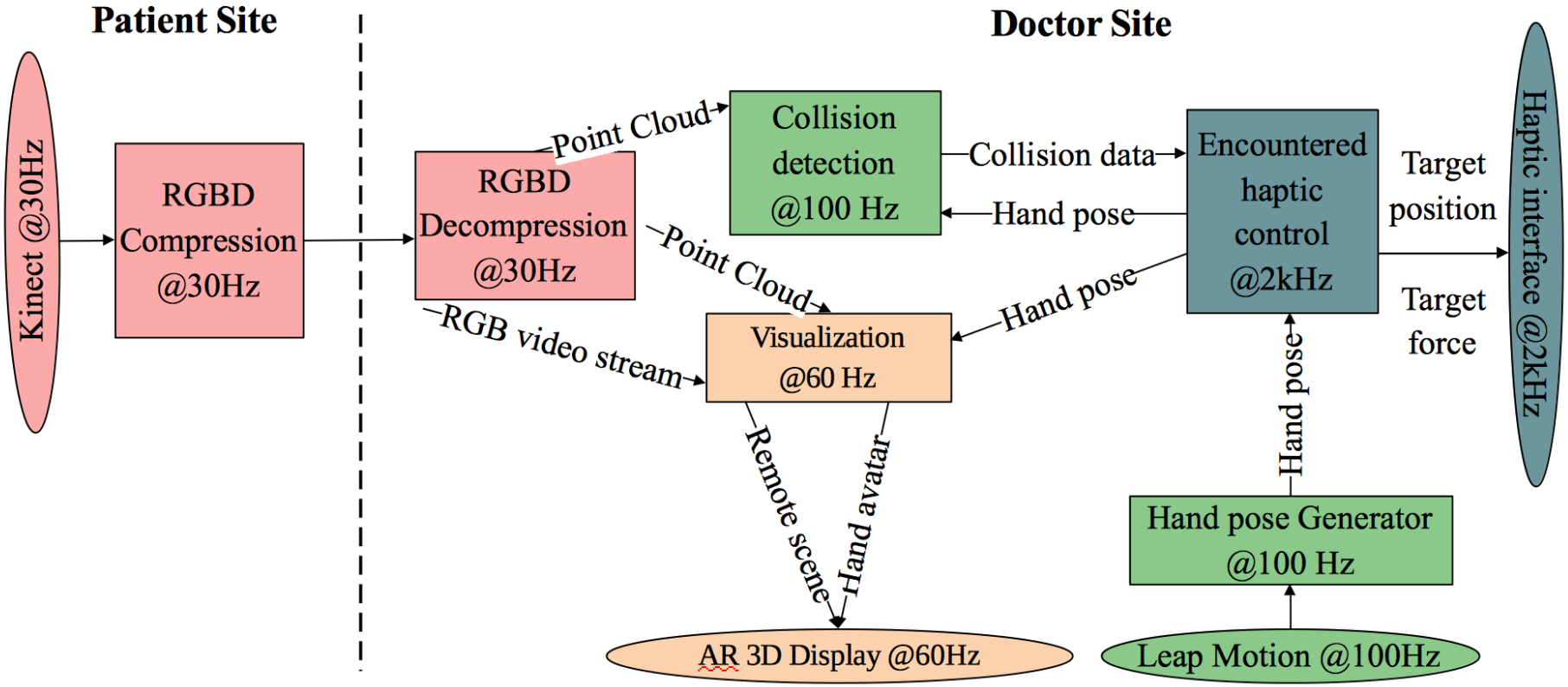
Leap Frame





Doctor Site

Data Streams and Processing



Co-located Augmented Reality

RGB-D scene rendered as 3D mesh

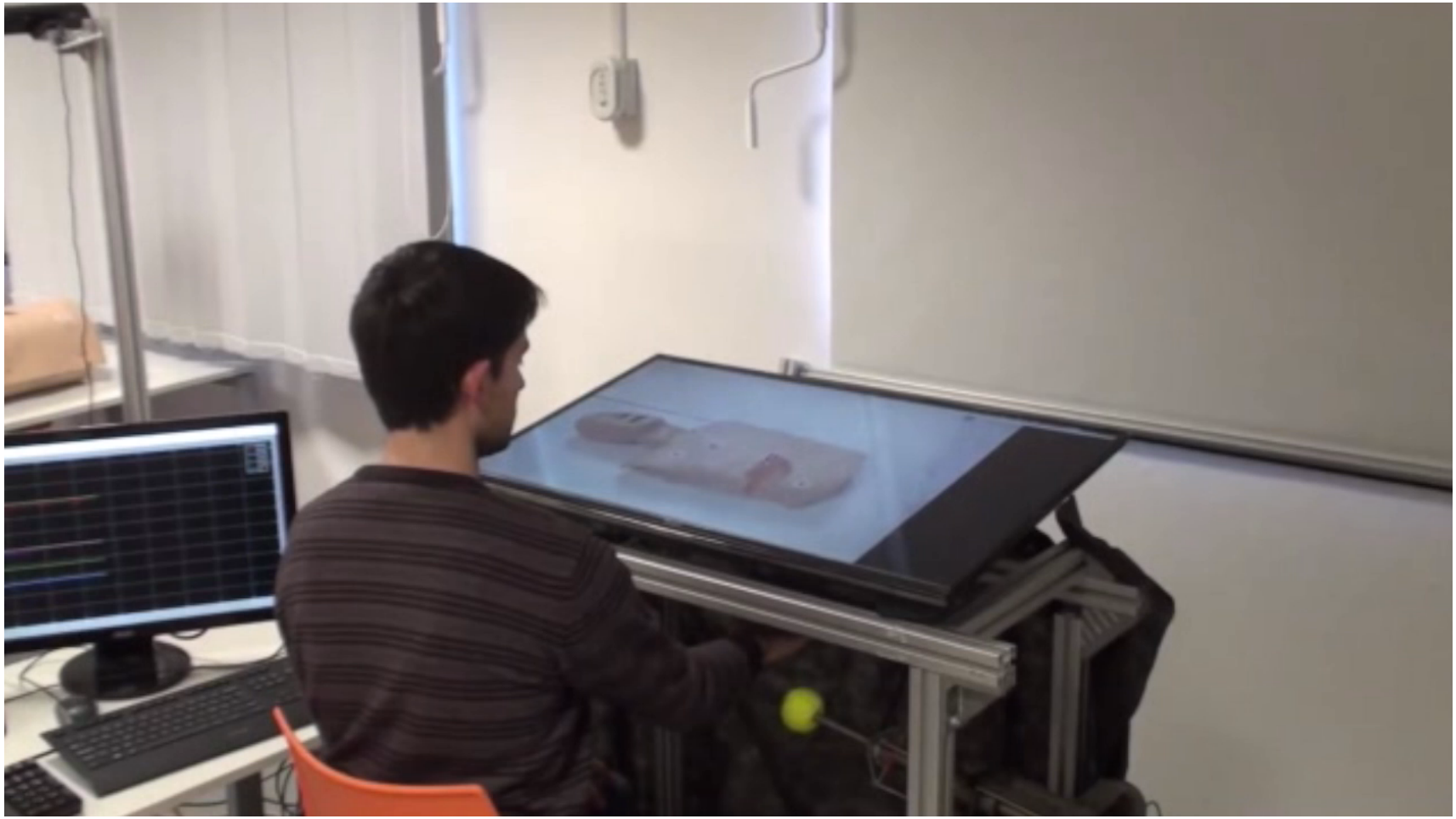
- Features:
  - RGBD NaN points reconstructed from interpolation
  - Fast CPU meshing
  - GPU based cleanup for removing too large triangles generated by distant points in the pointcloud
- Advantages
  - 3D visualization
  - Natural 3D augmentation, automatically handles occlusions
  - Support for changing point of view and extension to Oculus HMD [1]

Virtual hand

- 3D hand fixed model. In later work deformed from Leap Motion data
- Visual Hint: color shades to red the more the penetration in the surface

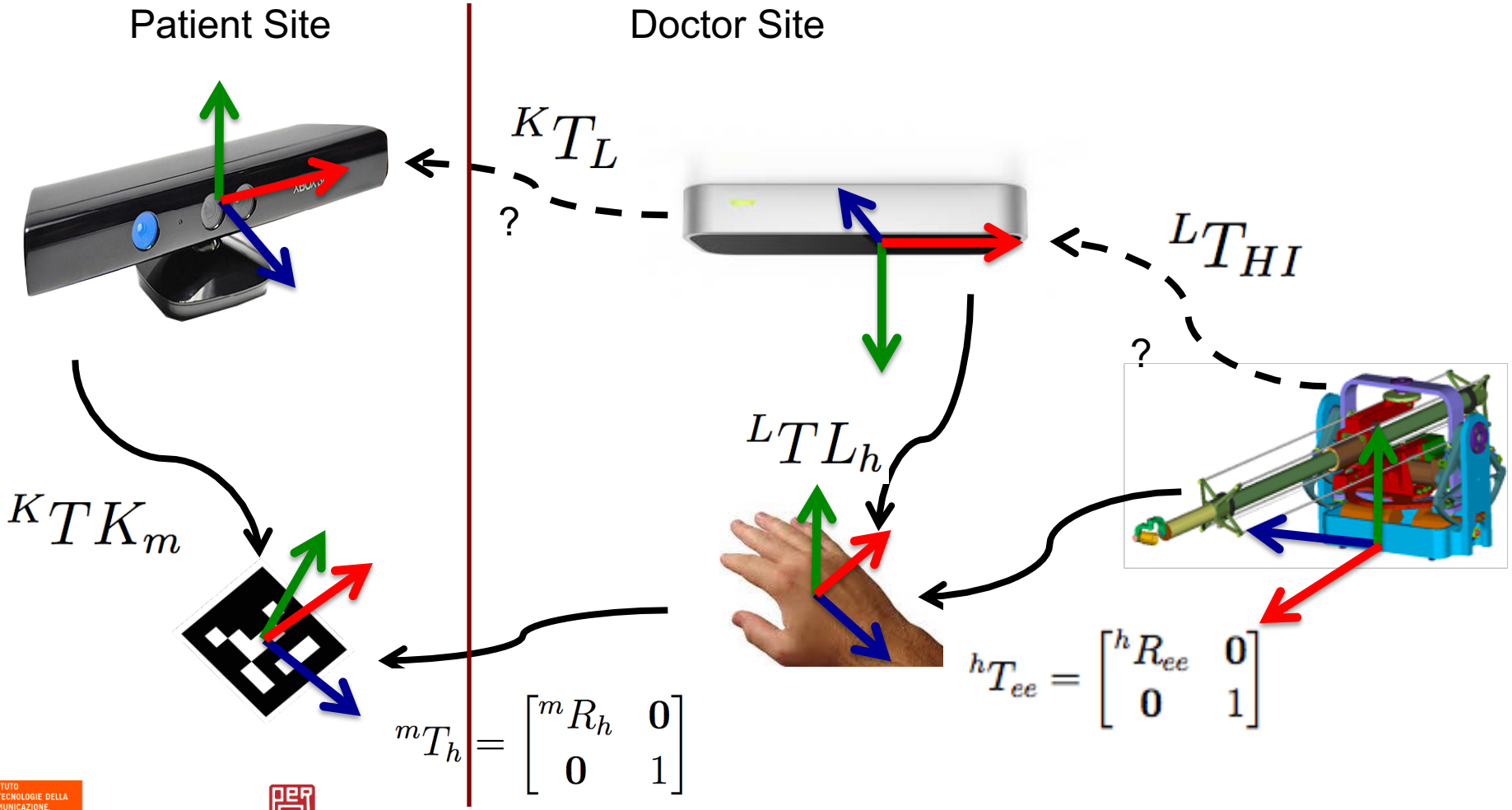
[1] Ruffaldi E., *Brizzi F.*, Filippeschi A. & Avizzano C.A. (2015). Co-Located haptic interaction for Virtual USG exploration. IEEE EMBC

Co-Located Augmented Reality

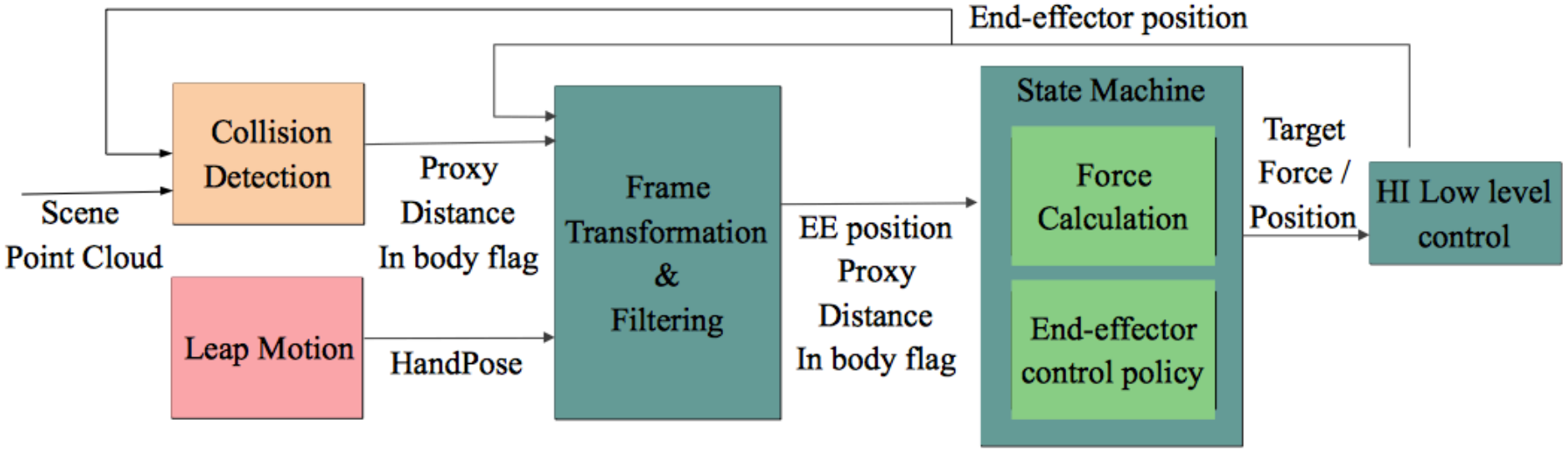


Obtaining Co-Location

Co-location requires calibration between the reference frames



Haptic Feedback



Collision Detection

Collision detection between the scene point cloud and the hand position

- Radius search on the KD-Tree built from the scene point cloud
  - Normal estimation of the contact surface
    - Implicit surface [1]
    - Proxy position [2]
  - Indentation value
  - In body / out body flag

[1] A. Adamson and M. Alexa, “Approximating and intersecting surfaces from points,” 2003
[2] K. Salisbury and C. Tarr, “Haptic rendering of surfaces defined by implicit functions,” 1997

Haptic Rendering

- End-effector position ${}^{H}\mathbf{pH}_{E}$
- Proxy position when first entering the surface ${}^{H}\mathbf{p}_{p}^{0}$

$$\mathbf{F} = [k_x(\mathbf{d}_x)k_y(\mathbf{d}_y)k_z(\mathbf{d}_z)]^T\mathbf{d}$$

$$k_i(d_i) = \alpha(d_i^2 + d_i) \quad \mathrm{i} = \mathrm{x,y,z}$$

$$\mathbf{d} = {}^{H}\mathbf{pH}_{E} - {}^{H}\mathbf{p}_{p}^{0}$$

- The output force depends on the proxy when first entering the surface

Encountered Interaction

Hand position from Leap Motion (100Hz)

- Kalman filter to stabilize and to sample at 2KHz

Virtual plane 1mm over the closest surface point to the camera

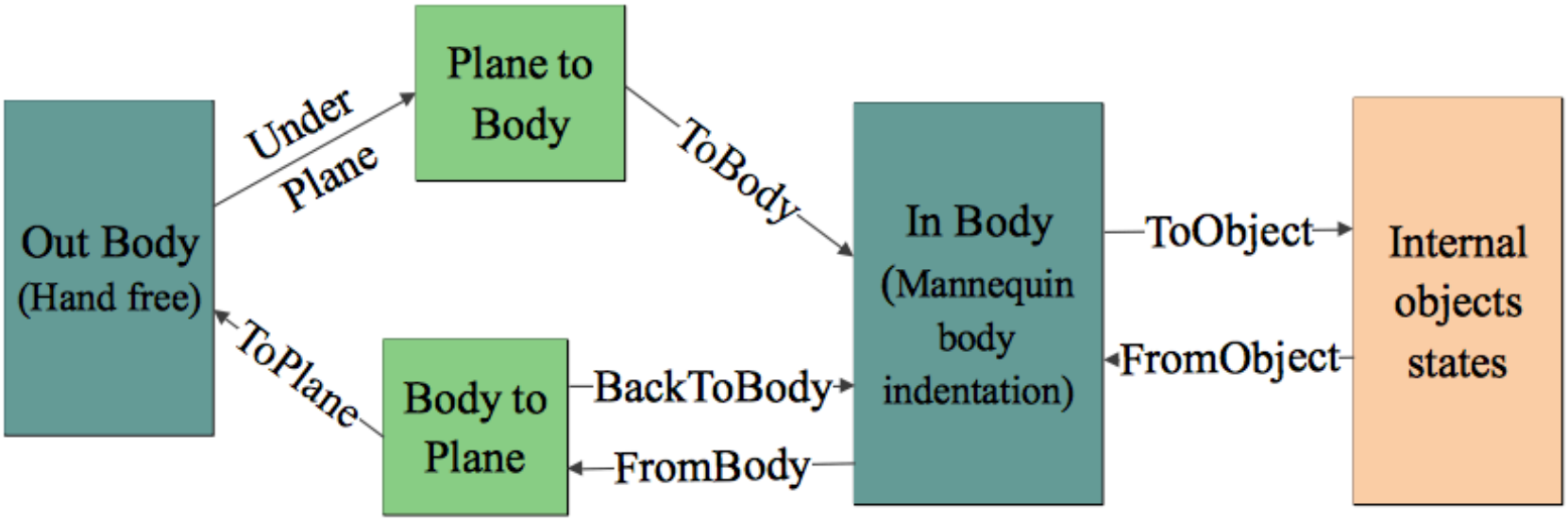
- End-effector moves on this plane according to XY coordinates from Leap Motion

Problem

- If the scene changes the plane needs to be updated
  - Computer Vision to estimate the new position

Dealing with In-Out transition

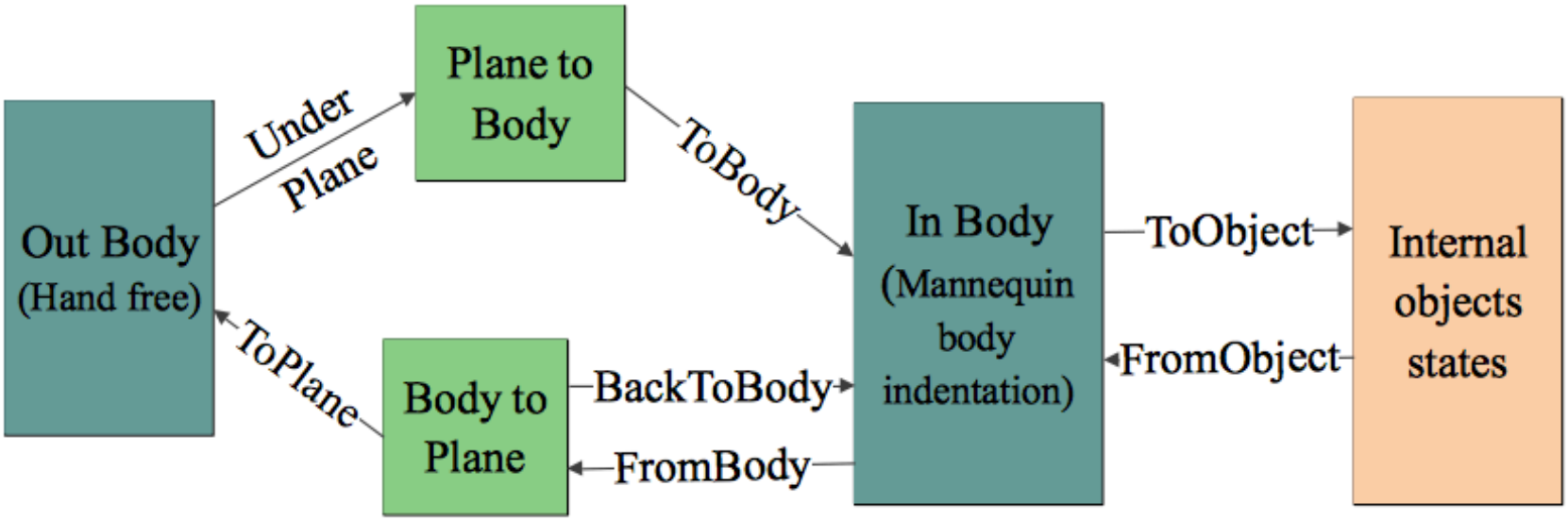
- Out Body
  - Hand moves freely and the EE follows it moving on a plane (EE in Position Control)
- In Body
  - Hand inside the surface and the EE provides the haptic feedback (EE in Force Control)



Dealing with In-Out transition

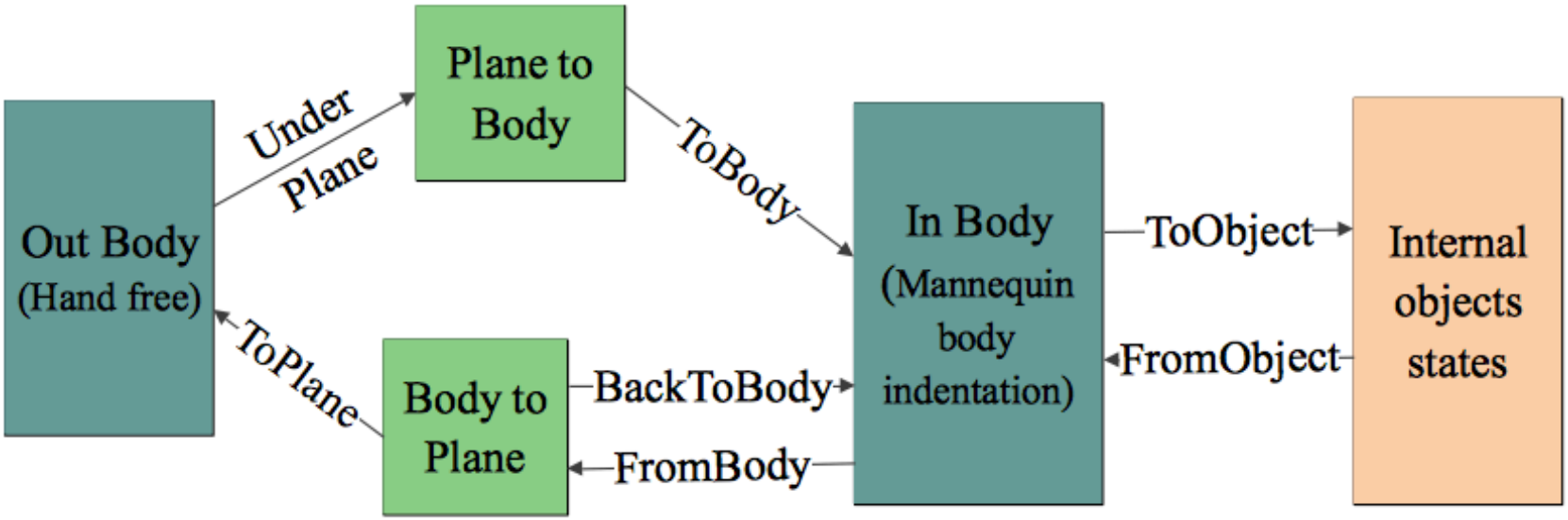
Controlling the instability when moving from out to in body and vice versa

- Minimum stay of 0.3 s in each state
- Two intermediate states when the EE is below the virtual plane but over surface



Dealing with In-Out transition

- Plane to Body
  - Gravity compensation.
  - EE waiting for being pushed down
- Body to Plane state
  - Small force applied to push the EE on the plane



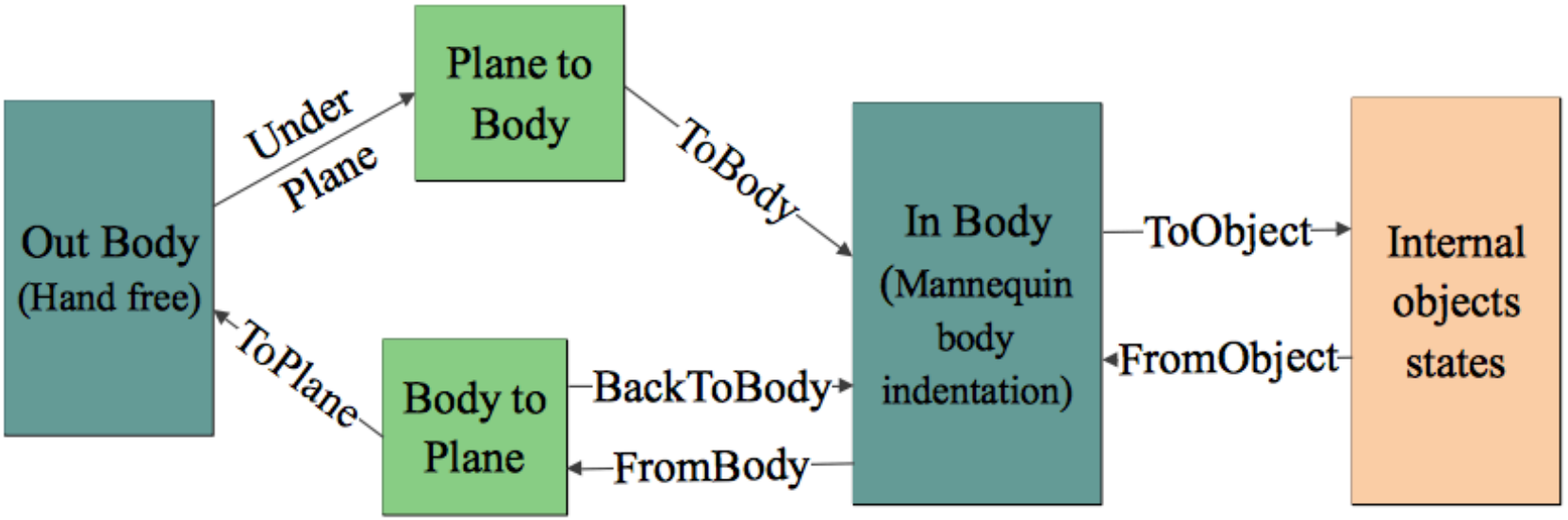
Add Abnormalities

Possibility to add virtual objects inside the surface

- Sphere or Cylinder
- Variable stiffness

Problem

- If the scene changes the objects needs to be updated
  - Computer Vision to estimate the new position



Haptic Interaction Video

System Evaluation

Experiment aimed at checking that forces are correctly displayed

- Natural interaction with the body.
- Identification of structures within the body.
  - A cylinder under the skin.
  - Much higher stiffness than the skin.

System Evaluation

$sf = 0$ i.e. *In body*;

$sf = 1$ i.e. *Body to Plane*;

$sf = 2$ i.e. *Out body*;

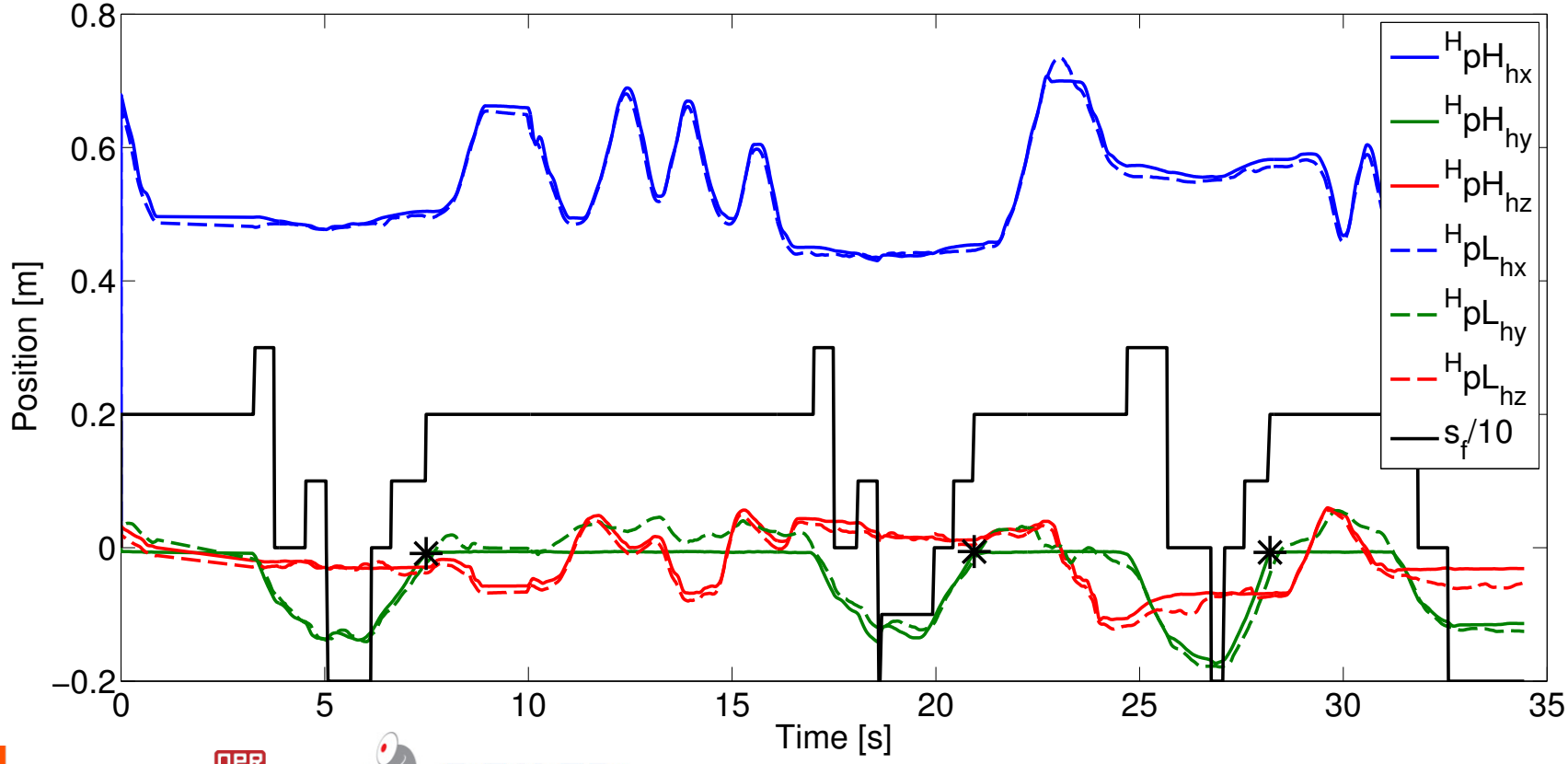
$sf = 3$ i.e. *Plane to Body*;

$sf = -3$ i.e. *Cylinder Upper Area*

$sf = -2$ i.e. *Around the Cylinder*;

$sf = -1$ i.e. *Cylinder LateralArea*

End effector positon against hand postion from Leap Motion



Indentation

$sf = 0$ i.e. *In body*;

$sf = 1$ i.e. *Body to Plane*;

$sf = 2$ i.e. *Out body*;

$sf = 3$ i.e. *Plane to Body*;

$sf = -3$ i.e. *Cylinder Upper Area*

$sf = -2$ i.e. *Around the Cylinder*;

$s\,f = -1$ i.e. *Cylinder LateralArea*

Conclusions

- Encountered is a promising approach for improving transparency
  - Especially coupled with Co-Located visualization
- Next
  - Integrate with Palpation End-Effector from ReMeDi
  - Deal with moving/deformable body thanks to Computer Vision based registration

http://www.remedi-project.eu/

Thanks!

- Questions?

- **Augmented Reality for Robotics**
  - **Open Special** issue on Frontiers in Robotics and Artificial Intelligence
  - Contact e.ruffaldi@sssup.it for details