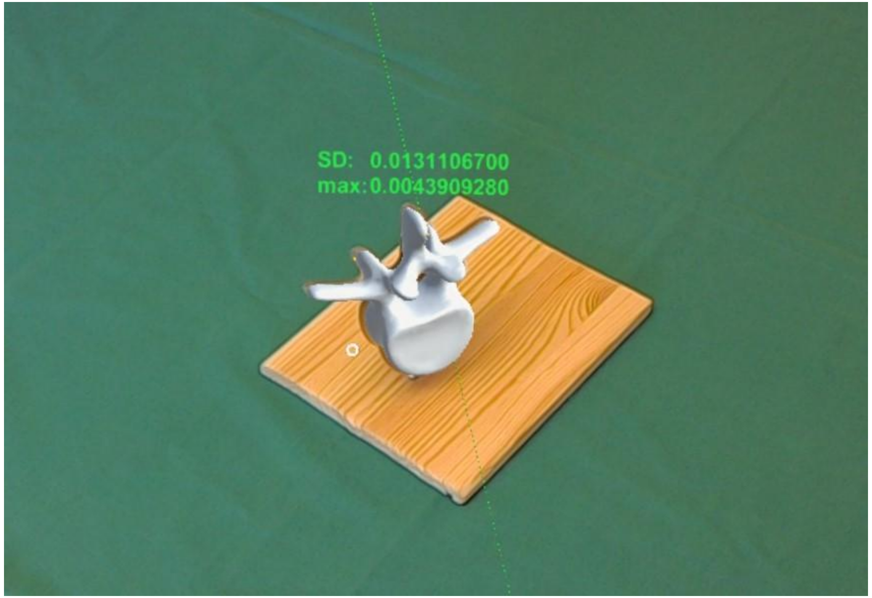
Augmented Reality for Surgical Navigation using HoloLens

Fabian Schneider - Bachelor Thesis

Overview

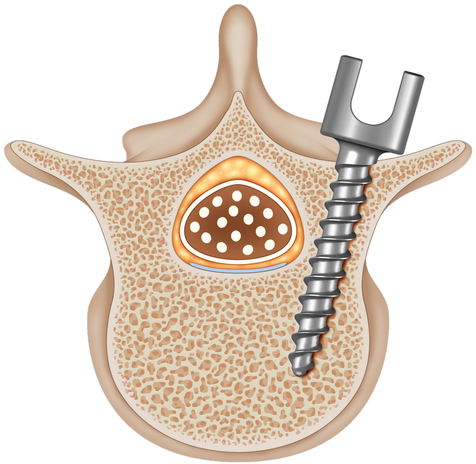


Introduction

Introduction - The clinical problem

- Pedicle screw placement
- Part of a procedure called spinal fusion - joining vertebras
- It is a common procedure and the vertebra exhibits very distinctive visual features that are exposed during surgery

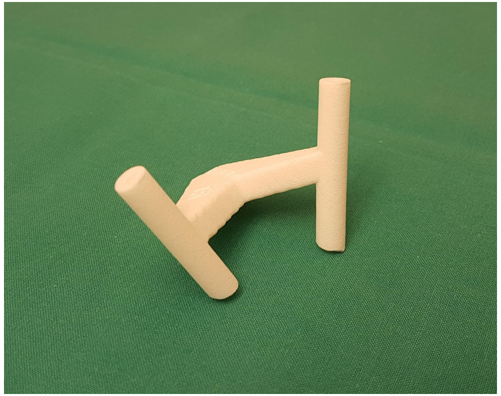
http://www.renovis-surgical.com/2011/09/s100-pedicle-screw-system/

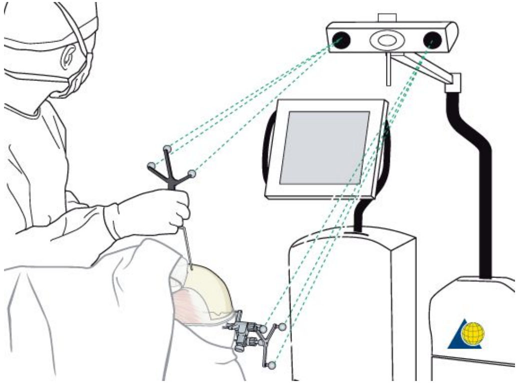


http://www.spineguard.com/wp-content/uploads/2016/03/Screw-Placements.png

Introduction - The clinical problem

- Intraoperative navigation - guided procedures
- Two concepts: Patient-specific guides and marker-based navigation





https://www2.aofoundation.org/AOFileServerSurgery/MyPortalFiles?FilePath=/Surgery/en/_img/9X-ComputerAssisted/X005/9X_X005_i330_540.gif

Introduction - Marker-based navigation system

+ Flexibility
+ More feedback, e.g. dynamic tool positioning

- Optical tracking - direct line of sight
- Interface sometimes complicated

Introduction - Patient-specific guides

+ Custom tailored for each patient
+ In-house 3D printed
+ Closely integrated into procedure planning

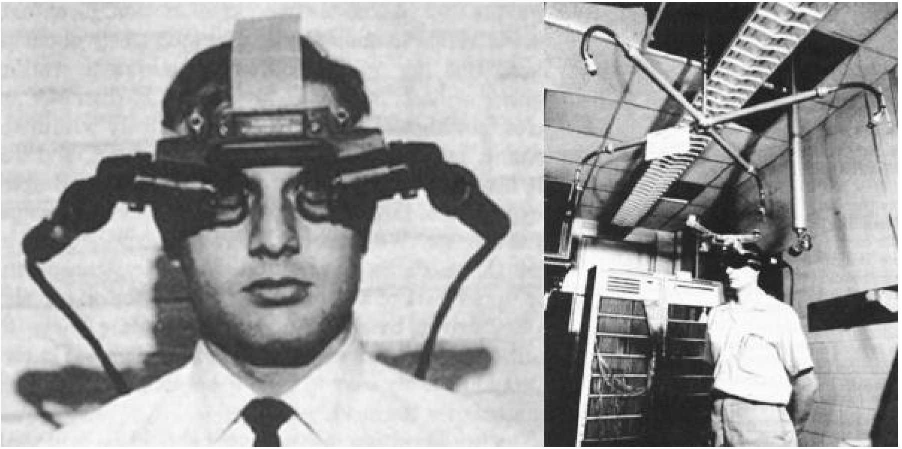
- Cost - custom modelling
- No flexibility during surgery

Introduction - Augmented Reality Display

https://www.youtube.com/watch?v=NtwZXGprxag

Introduction - Augmented Reality in Medicine

- Head-mounted 3D display by Sutherland in 1968
- Computational power is still limited
- First CT devices in 1972
- Good 3D scans not possible before the 1990s, voxel based representation
- Hence in the 1990s we have the stage set for medical application



https://alchetron.com/Ivan-Sutherland-839213-W#-

Introduction - Augmented Reality in Medicine

- In the 1990s and 2000s field became very active
- Stereoscopic instruments leveraged, HMDs, Mirror-based display systems
- Visual markers, IR markers, camera-tracking and external IR tracking
- Integrated medical imagery devices: MRI, PET, X-ray, ultra-sound
- Registration is the issue
- Most recent: L. Ma et al. , 2017, propose marker-free, ultra-sound guided registration for pedicle screw placement
- J. Wang et al., 2014, “Augmented Reality Navigation With Automatic Marker-Free Image Registration Using 3D Image Overlay for Dental Surgery”, 0.71 mm overlay accuracy using stereo camera system

Introduction - Augmented Reality in Medicine

- Nowadays in practice the research resulted in highly integrated “hybrid operating theatres”. Tracking, C-arm X-Ray, HMD sold as complete system.
- Nassir Navab’s group at TUM has a tremendous output of relevant work in this field: X-ray vision, Hand-held tracked X-ray

https://www.philips.com/c-dam/corporate/newscenter/global/standard/resources/healthcare/2017/augmented-reality-surgical-navigation-technology/Philips-Hybrid-Operating-Room-with-Surgical-Navigation-Technology-1.jpg

http://campar.in.tum.de/Chair/ProjectMedUI

Introduction - How does this work fit in?

- Feasibility - Let’s see what we can do with the HoloLens NOW
- Rely on given built-in tracking and camera pose estimation
- 3D model registration is the task to solve - using that we can build a lot more
- Assumptions: Static patient, line of sight to target object
- Pedicle screw placement - direct line of sight, distinctive features of vertebra exposed

Introduction - Some first ideas

- Machine learning - find rotation of real object relative to camera, pre-train on existing 3D model
- Structure from motion - use built-in sensors and camera pose estimation to generate high quality point cloud
- Attach more sensors, e.g. Kinect v2 - Communicate over network… latency!

Holographic Application

Holographic Application - HoloLens

- 1 Depth camera
- 4 environment understanding cameras
- 1 RGB HD video/RGB 2MP photo camera
- 1 ambient light sensor
- 1 inertial measurement unit

https://az835927.vo.msecnd.net/sites/mixed-reality/Resources/images/Sensor_bar.jpg

Holographic Application - Terminology

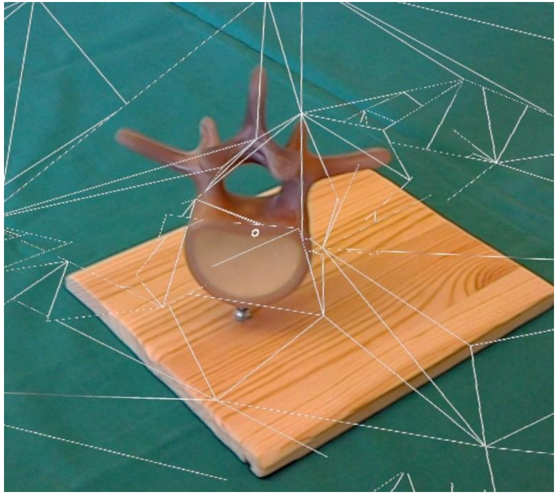
- Spatial Coordinate System - HoloLens' coordinate system, scaled to match real world
- Spatial Map - 3D Reconstruction of the real world, triangle mesh
- Holograms - 3D objects rendered in the user's field of view (not a 3D object encoded on 2D surface!)
- Spatial Anchor - Important point in the world that the system should keep track of

Holographic Application - Testbed

- 3D printed human adult vertebra
- Many good visual features
- Distinctive shape
- Attached to a wooden board to keep it stable

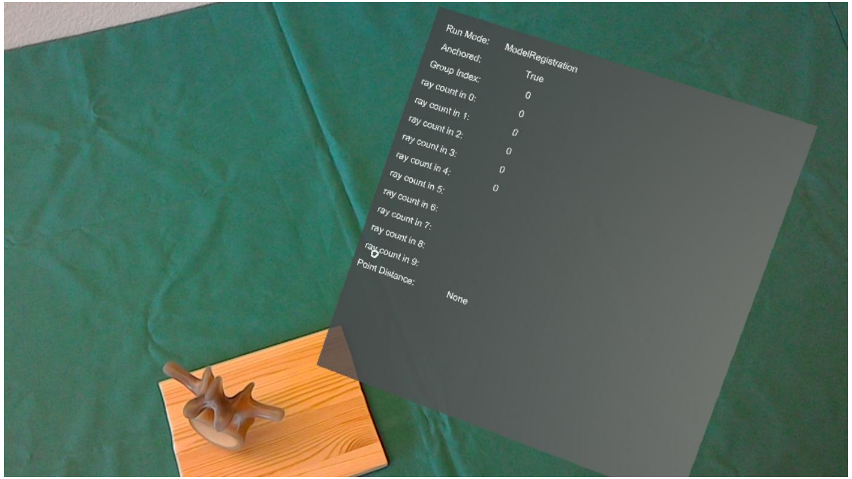
Holographic Application - The spatial map

- One of the first ideas: Why not use the spatial reconstruction as a source for point clouds?
- The reconstruction is not detailed enough for complex geometry and small objects



Holographic Application - Billboarded 3D Text

- HUD displays are difficult: Focal distance
- Billboarding: A technique promoted by Microsoft as best-practice
- Object containing information is rotated to face the user orthogonally
- Can of course be replaced quickly using spatial map
- Great plus: Information can be placed at roughly same focal distance as target area



Holographic Application - Voice recognition

- Keyword recognition
- Needs internet connection
- Very powerful and high recognition rate
- Most of the input to the app is through voice
- Great plus: Hands-free, perfect for surgery
- Problem: In our case for ray shooting reaction time is better with the clicker
- Problem (maybe): for now English only

https://i2.wp.com/techbonza.com/wp-content/uploads/2015/12/cortana.png?resize=1024%2C532

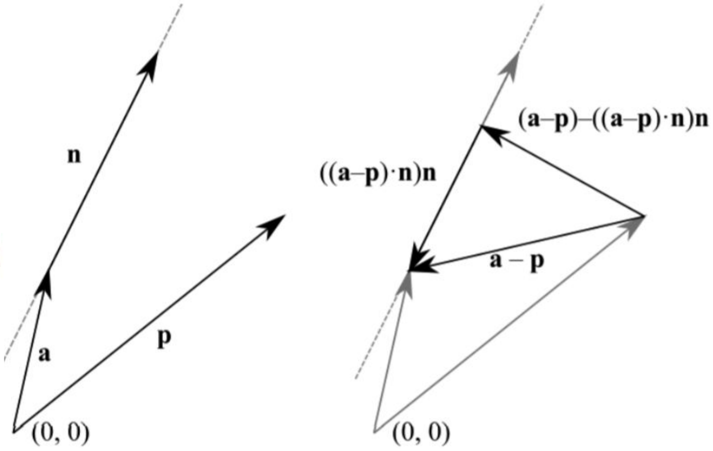
Holographic Application - Define a single point

Let $\boldsymbol{a} \in \mathbb{R}^3$ a point (in our case the HoloLens position), $\boldsymbol{n} \in \mathbb{R}^3, \|\boldsymbol{n}\|_2 = 1$ a direction vector (in our case the viewing direction). This defines a line

$$\boldsymbol{l} = \boldsymbol{a} + t \cdot \boldsymbol{n}, \quad -\infty < t < \infty$$

Holographic Application - Define a single point

$$
\begin{aligned}
D(\boldsymbol{p};\boldsymbol{a},\boldsymbol{n}) &= \|(\boldsymbol{a}-\boldsymbol{p})-((\boldsymbol{a}-\boldsymbol{p})^T\boldsymbol{n})\boldsymbol{n}\|_2^2 \\
&= \|(\boldsymbol{a}-\boldsymbol{p})-\boldsymbol{n}\boldsymbol{n}^T(\boldsymbol{a}-\boldsymbol{p})\|_2^2 \\
&= \|(\boldsymbol{I}-\boldsymbol{n}\boldsymbol{n}^T)(\boldsymbol{a}-\boldsymbol{p})\|_2^2 \\
&= (\boldsymbol{a}-\boldsymbol{p})^T(\boldsymbol{I}-\boldsymbol{n}\boldsymbol{n}^T)(\boldsymbol{I}-\boldsymbol{n}\boldsymbol{n}^T)^T(\boldsymbol{a}-\boldsymbol{p}) \\
&= (\boldsymbol{a}-\boldsymbol{p})^T(\boldsymbol{I}-\boldsymbol{n}\boldsymbol{n}^T)(\boldsymbol{a}-\boldsymbol{p})
\end{aligned}
$$



Holographic Application - Define a single point

$$D(\boldsymbol{p}; \boldsymbol{A}, \boldsymbol{N}) = \sum_{i=1}^{k} D(\boldsymbol{p}; \boldsymbol{a}_i, \boldsymbol{n}_i) = \sum_{i=1}^{k} (\boldsymbol{a}_i - \boldsymbol{p})^T (\boldsymbol{I} - \boldsymbol{n}_i \boldsymbol{n}_i^T)(\boldsymbol{a}_i - \boldsymbol{p})$$

$$\frac{\partial D}{\partial \boldsymbol{p}} = \sum_{i=1}^{k} -2(\boldsymbol{I} - \boldsymbol{n}_i \boldsymbol{n}_i^T)(\boldsymbol{a}_i - \boldsymbol{p}) = 0$$

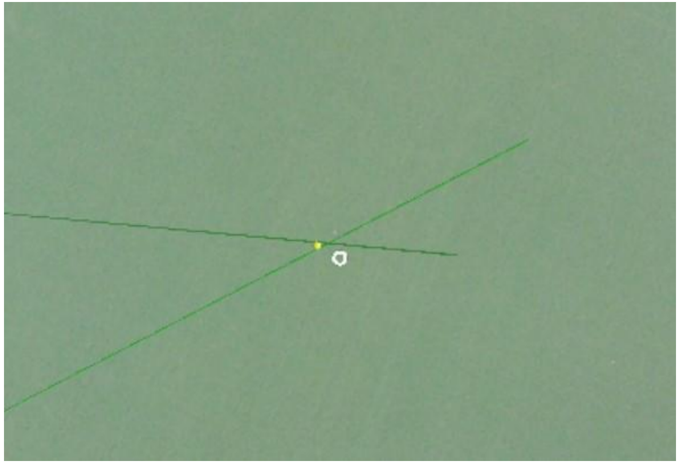
Holographic Application - Define a single point

$$\boldsymbol{Rp} = \boldsymbol{q}, \boldsymbol{R} = \sum_{i=1}^{k}(\boldsymbol{I} - \boldsymbol{n}_i\boldsymbol{n}_i^T), \boldsymbol{q} = \sum_{i=1}^{k}(\boldsymbol{I} - \boldsymbol{n}_i\boldsymbol{n}_i^T)\boldsymbol{a}_i$$

$$\boldsymbol{p} = \boldsymbol{R}^{-1}\boldsymbol{q}$$

Holographic Application - Define a single point

- Used this method to define a point in spatial coordinate system for every landmark given by the 3D model
- Hence we now have two corresponding point clouds



Holographic Application - Absolute Orientation

$$e_i = p_{r,i} - Rp_{l,i} - t$$

$$\sum_{i=1}^{n} ||e_i||_2^2$$

Holographic Application - Absolute Orientation

$$\mu_l = \frac{\sum_{i=1}^{n} p_{l,i}}{n}, \quad \mu_r = \frac{\sum_{i=1}^{n} p_{r,i}}{n}$$

$$p'_{l,i} = p_{l,i} - \mu_l, \quad p'_{r,i} = p_{r,i} - \mu_r$$

$$e_i = p'_{r,i} - Rp'_{l,i} - t', \quad t' = t - \mu_r + R\mu_l$$

Holographic Application - Absolute Orientation

$$
\begin{aligned}
\sum_{i=1}^{n} \|\boldsymbol{e}_i\|_2^2 &= \sum_{i=1}^{n} \|\boldsymbol{p}'_{r,i} - \boldsymbol{R}\boldsymbol{p}'_{r,i} - \boldsymbol{t}'\|_2^2 \\
&= \sum_{i=1}^{n} \|\boldsymbol{p}'_{r,i} - \boldsymbol{R}\boldsymbol{p}'_{l,i}\|_2^2 - 2\boldsymbol{t}' \cdot \sum_{i=1}^{n} [\boldsymbol{p}'_{r,i} - \boldsymbol{R}\boldsymbol{p}'_{l,i}] + n\|\boldsymbol{t}'\|_2^2
\end{aligned}
$$

Holographic Application - Absolute Orientation

$$\boldsymbol{t} = \boldsymbol{\mu}_r - \boldsymbol{R}\boldsymbol{\mu}_l$$

$$\sum_{i=1}^{n} ||\boldsymbol{p}'_{r,i} - \boldsymbol{R}\boldsymbol{p}'_{r,i}||_2^2 = \sum_{i=1}^{n} ||\boldsymbol{p}'_{r,i}||_2^2 - 2\sum_{i=1}^{n} \boldsymbol{p}'_{r,i} \cdot \boldsymbol{R}\boldsymbol{p}'_{l,i} + \sum_{i=1}^{n} ||\boldsymbol{R}\boldsymbol{p}'_{l,i}||_2^2$$

Holographic Application - Absolute Orientation

$$-2\sum_{i=1}^{n} \boldsymbol{p}'_{r,i} \cdot \boldsymbol{R}\boldsymbol{p}'_{l,i} = -2\sum_{i=1}^{n} \boldsymbol{p}'_{r,i} \cdot (\boldsymbol{q} * \boldsymbol{p}'_{l,i} * \overline{\boldsymbol{q}}) = -2\sum_{i=1}^{n} (\boldsymbol{q} * \boldsymbol{p}'_{l,i} * \overline{\boldsymbol{q}}) \cdot \boldsymbol{p}'_{r,i} = -2\sum_{i=1}^{n} (\boldsymbol{q} * \boldsymbol{p}'_{l,i}) \cdot (\boldsymbol{p}'_{r,i} * \boldsymbol{q})$$

Holographic Application - Absolute Orientation

$$\boldsymbol{p}'_{r,i} * \boldsymbol{q} = \begin{bmatrix} 0 & -x'_{r,i} & -y'_{r,i} & -z'_{r,i} \\ x'_{r,i} & 0 & -z'_{r,i} & y'_{r,i} \\ y'_{r,i} & z'_{r,i} & 0 & -x'_{r,i} \\ z'_{r,i} & -y'_{r,i} & x'_{r,i} & 0 \end{bmatrix} \boldsymbol{q} = \boldsymbol{P}'_{r,i}\boldsymbol{q}$$

$$\boldsymbol{q} * \boldsymbol{p}'_{l,i} = \boldsymbol{q} \begin{bmatrix} 0 & -x'_{r,i} & -y'_{r,i} & -z'_{r,i} \\ x'_{r,i} & 0 & -z'_{r,i} & -y'_{r,i} \\ y'_{r,i} & -z'_{r,i} & 0 & x'_{r,i} \\ z'_{r,i} & y'_{r,i} & -x'_{r,i} & 0 \end{bmatrix} = \overline{\boldsymbol{P}'_{l,i}}\boldsymbol{q}$$

Holographic Application - Absolute Orientation

$$\begin{aligned}
\sum_{i=1}^{n}(q * p'_{l,i}) \cdot (p'_{r,i} * q) &= \sum_{i=1}^{n}(\overline{P'_{l,i}}q) \cdot (P'_{r,i}q) \\
&= \sum_{i=1}^{n}(\overline{P'_{l,i}}q)^T (P'_{r,i}q) \\
&= \sum_{i=1}^{n} q^T \overline{P'_{l,i}}^T P'_{r,i} q \\
&= q^T \sum_{i=1}^{n}(\overline{P'_{l,i}}^T P'_{r,i}) q
\end{aligned}$$

Holographic Application - Absolute Orientation

$$\boldsymbol{N} = \sum_{i=1}^{n} \overline{\boldsymbol{P}'_{l,i}}^{T} \boldsymbol{P}'_{r,i}$$

$$\boldsymbol{N}\boldsymbol{v_i} = \boldsymbol{\lambda}_i \boldsymbol{v_i}, \quad \text{for } i = 1, \ldots, 4$$

$$\boldsymbol{q} = \sum_{i=1}^{4} \alpha_i \boldsymbol{v_i}$$

$$\boldsymbol{q} \cdot \boldsymbol{q} = \sum_{i=1}^{4} \alpha_i^2 = 1$$

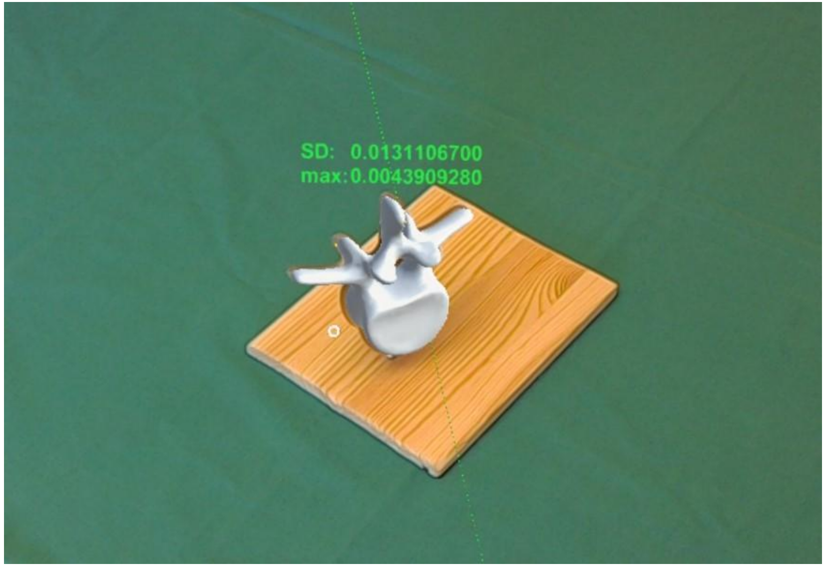
Holographic Application - Absolute Orientation

$$\boldsymbol{N}\boldsymbol{q} = \boldsymbol{N}\sum_{i=1}^{4}\alpha_i\boldsymbol{v_i} = \sum_{i=1}^{4}\alpha_i\lambda_i\boldsymbol{v_i}$$

$$\boldsymbol{q}^T\boldsymbol{N}\boldsymbol{q} = \sum_{i=1}^{4}\alpha_i^2\lambda_i$$

$$\boldsymbol{q}^T\boldsymbol{N}\boldsymbol{q} \leq \sum_{i=1}^{4}\alpha_i^2\lambda_1 = \lambda_1\sum_{i=1}^{4}\alpha_i^2 = \lambda_1$$

Holographic Application - Overlay the vertebra



Holographic Application - What ‘s it good for?

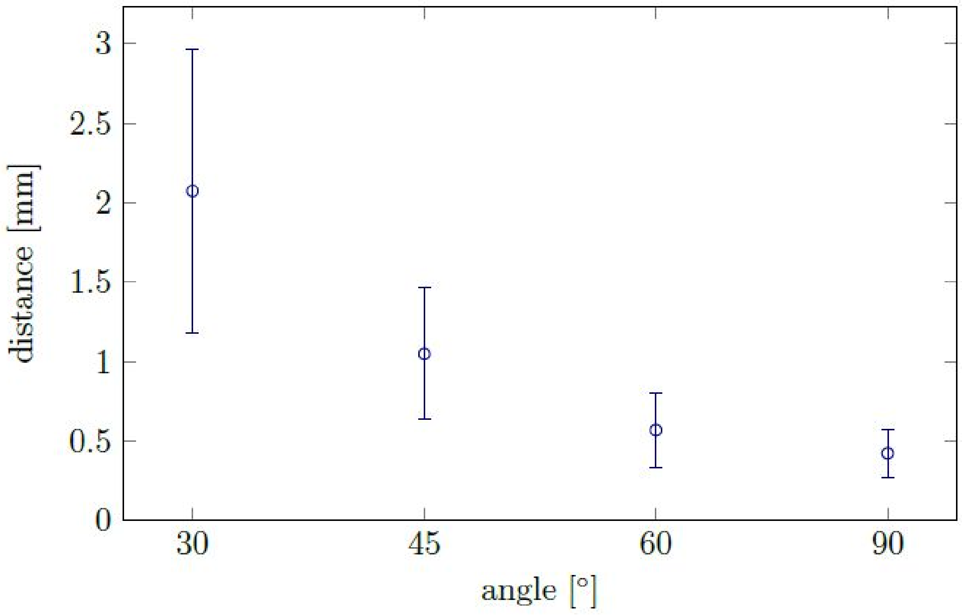
- Now the HoloLens knows where the object of interest is
- Target has to be static, otherwise useless
- Not done in this work - Do whatever one imagines using the registered model
- E.g. show metadata at the right spot
- E.g. show surgical procedure instructions
- E.g. show explosion model of the object
- ...

Evaluation

Evaluation - Experiment: Single point definition

- Virtual target point, about 1 m above ground
- What error distances do we get?
- Do error distances get smaller when angles are increased?
- Does the error distance get smaller using more rays?

Evaluation - Results using 2 rays



Evaluation - Results using 2 rays

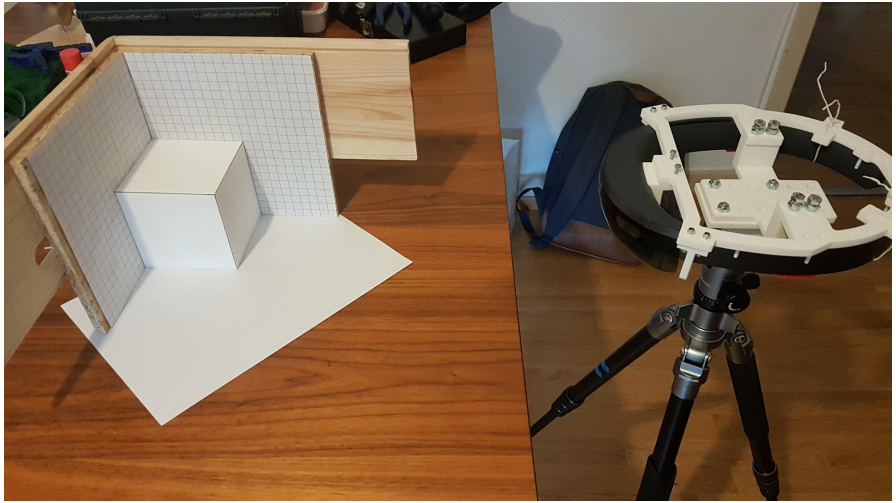
- Using two rays: Increasing angles 30, 45, 60, 90 degrees result in ever better error distance
- **Mean** error distance for 30 deg.: 2.074 mm
- **Variance** for error distance for 90 deg.: 0.892 mm
- **Mean** error distance for 90 deg.: **0.424 mm**
- **Variance** for error distance for 90 deg.: **0.154 mm**

Evaluation - Results using 3 rays

- Using three mutually orthogonal (approx.) rays
- **Mean** error distance for 90 deg.: **0.429 mm**
- **Variance** for error distance for 90 deg.: **0.287 mm**
- Mean stayed roughly the same
- Variance doubled

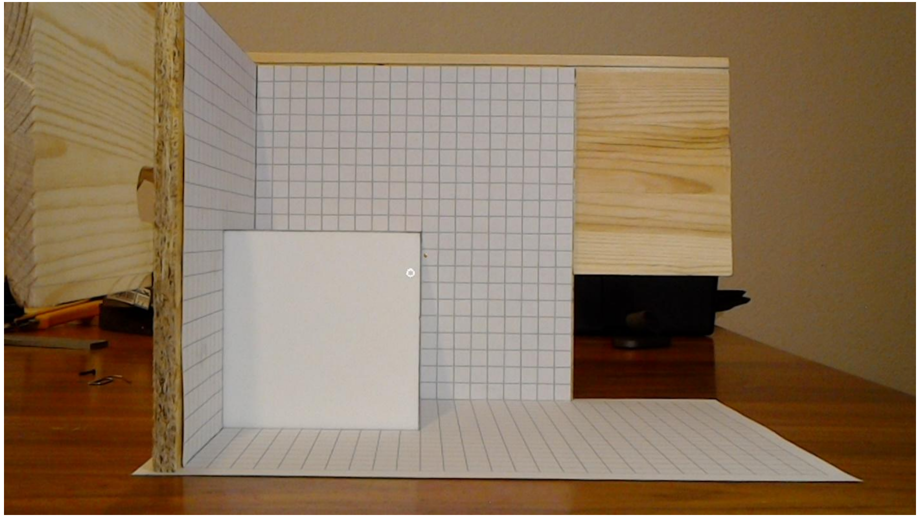
Evaluation - Experiment: Accuracy

- Does a user defined point actually overlay the real world target?
- Constructed a target setup which makes alignment easier
- Used three rays, at least 60 degrees between the rays



Evaluation - Experiment: Accuracy

- Measured distance afterwards using ImageJ
- Defined scale using pixel-scale probe and the front-facing cube edge (which is 100 mm)



Evaluation - Results

- Points shifted a lot between measurements and repositioning of the HoloLens
- Should I rather find a place where tracking is better? - NO! This would be fitting data/experiment to desired results
- Actually gives a pretty could estimate of what to expect

View	(μ_x, μ_y) [(cm,cm)]	(σ_x, σ_y) [(cm,cm)]
Front	(0.1768, 0.7038)	(0.1463, 0.3363)
Side	(0.6469, 0.2032)	(0.1246, 0.2285)
Top	(0.6060, 0.6242)	(0.1254, 0.1103)

Evaluation - Experiment: Timing

- Used simplistic method using navigational hand gestures to rotate and drag 3D model
- Had to introduce upper bound on time spent using this simple method

Evaluation - Results

- It's just quicker and easier (for me)

SD [mm] μ	SD [mm] σ	Max [mm] μ	Max [mm] σ
42.7718	19.4891	13.2501	8.0937

Simplistic method

SD [mm] μ	SD [mm] σ	Max [mm] μ	Max [mm] σ
3.2477	0.75312	0.8631	0.4083

Our method

Evaluation - Conclusions

- Method is precise w.r.t. virtual targets
- Placing a hologram is much easier and quicker compared to standard gestures
- Accuracy experiment w.r.t. real target might have systematic error
- ... or be heavily influenced by tracking system.
- ... or the method just has flaws. Hard to say from this experiment
- Obviously too unreliable to even come close to an operating theatre

Future Work

Future Work

- This can be used as a building block for AR related research
- E.g. assume a registered vertebra model, what crucial information should be shown?
- In general, find out what benefits most when being augmented
- Evaluate how marker-based tracking could perform on HoloLens

Summary

Summary

- Being independent of any external tracking makes HoloLens a cheap entry device
- Our work can be used as a stepping stone for AR related research in medicine
- The method is precise and computationally cheap, but completely static
- Depends on device’s capabilities

Lessons learned

Lessons learned

- Scientific work
- Think of experiments early on
- Experiments can be involving - Spend time in construction stores
- Time estimation and order of tasks
- LaTex
- Storytelling and the big picture

Thank you for listening!
Now a quick demo

Questions?