Computer Aided Medical Procedures

Master Thesis Presentation

Integration of RGBD Camera and Mobile C-arms - Calibration, Accuracy and Application

LEE Sing Chun

Advisor: Prof. Dr. Nassir Navab

Supervisor: Bernhard Fuerst

Montag, 15. Februar 2016

Technische Universität München

+

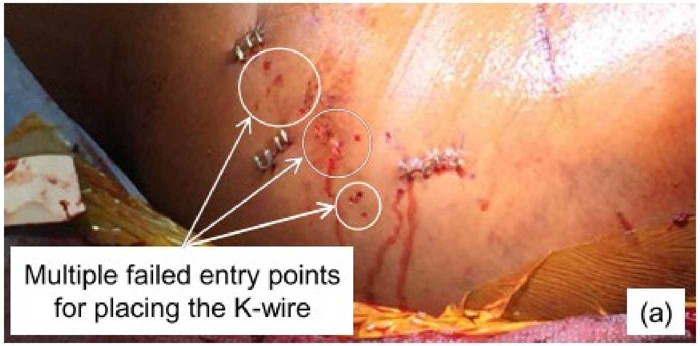
Johns Hopkins Whiting School of Engineering

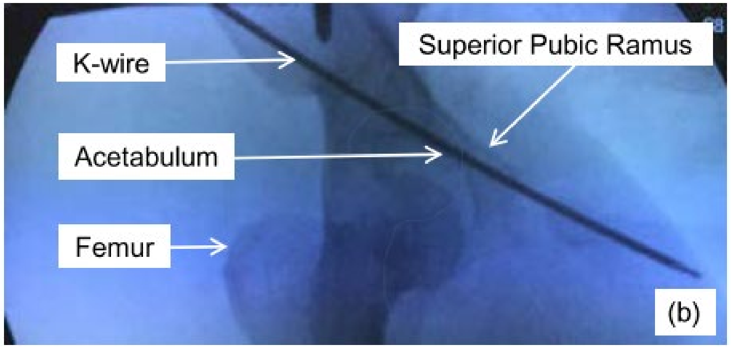
Outline

- Problem Statement & State of the Art
- System Setup
- Calibration Method
- Visualization
- Results and Applications
- Pre-clinical Usability Study
- Evaluation Results
- Discussion and Future Work

Problem Statement: Clinical Background

- Improved treatment outcome ➔ minimal invasive surgery is a current trend
- Limited field of views ➔ imaging techniques are imposed

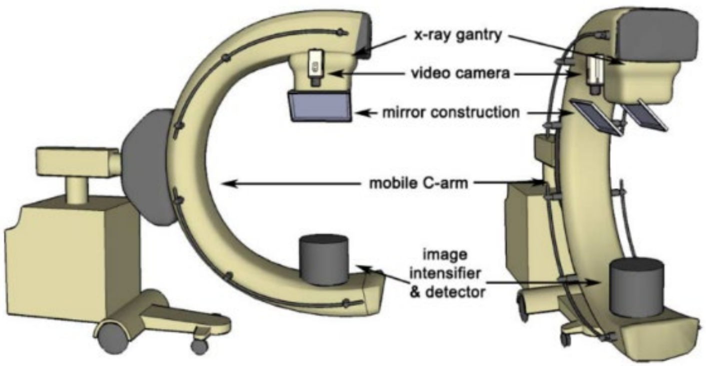




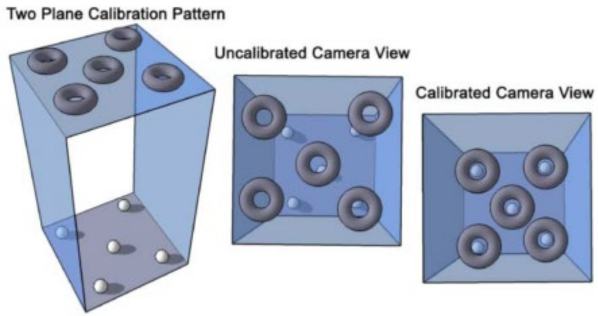
- In orthopedic and trauma surgery, X-ray imaging is frequently used
  - Anatomical information ➔ entry point localization
  - Require many X-rays from different prospective
- Clinical interests:
  - Shorter operation time
  - Less radiation dose
  - More accurate entry point localization
  - Easier and more intuitive information assess
- ***Desire to provide depth information*** in operation room from the imaging

State of the Art: RGB Camera (2D) to X-Ray (2D)

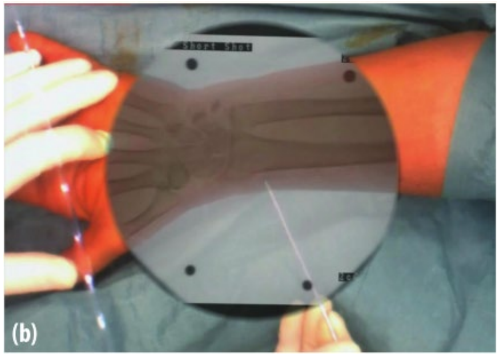
- Camera Augmented Mobile C-Arm (CAMC)[1]
  - Rigidly mounted RGB camera on C-arm
  - Co-centric optical centers (by double mirror)
  - Estimate the homography transformation
  - Overlay of live RGB and x-ray
  - Accuracy of < 1 mm



✓ Pros
  - Simple one-time calibration
  - **Live visual feedback** on top of x-ray
  - Reduced number of x-rays



✗ Cons
  - Upside down design and reduced working space
  - **Lack of depth information** from one single x-ray
  - Overlay is outdated when C-arm is moved
  - Tool occlusion in follow-up x-rays



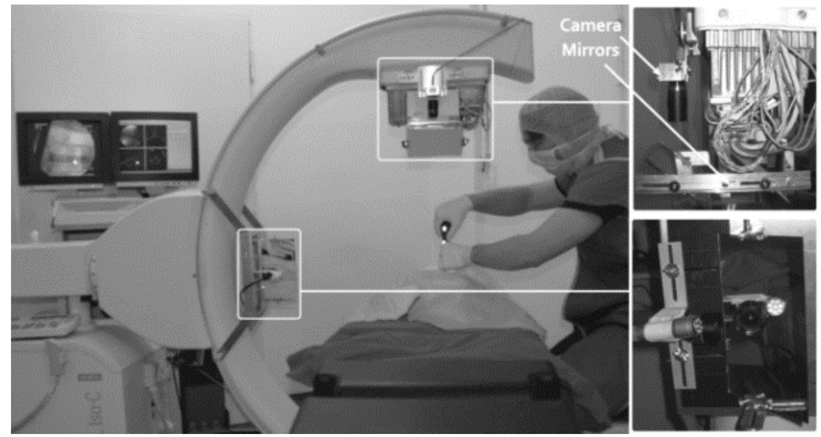
[1]Navab, N.; Heining, S.-M.; Traub, J., "Camera Augmented Mobile C-Arm (CAMC): Calibration, Accuracy Study, and Clinical Applications," in *IEEE Transactions on Medical Imaging,* 2010

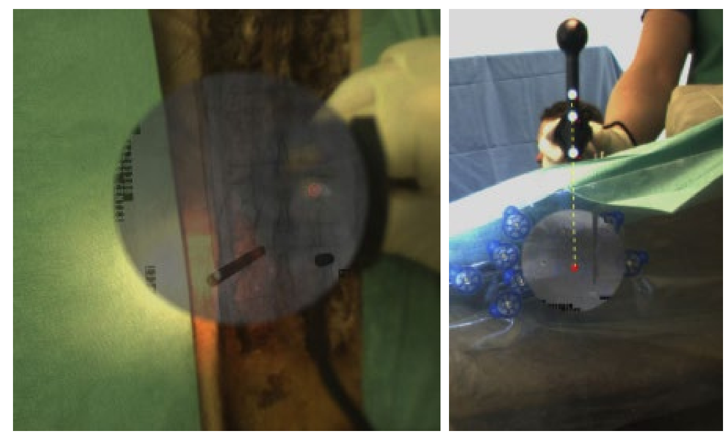
State of the Art: 2 RGB Cameras (2D) to X-Ray (2D)

- CAMC with opto-view[2]
  - CAMC + RGB mounted on opto-view
  - Additional calibration for the 2nd camera
  - 2 X-rays and 2 overlays (opto-views)
  - Tool tracking for augmentation

✓ Pros
  - Simple add-ons and a one-time calibration
  - Live visual feedback in both views
  - Reduced number of x-rays
  - **Provides depth feedback** by tracking tools

✗ Cons
  - Upside down design and reduced working space
  - Overlays are outdated when C-arm is moved
  - **Line-of-sight problem**
  - **Need to acquire opto x-ray by manual movement**

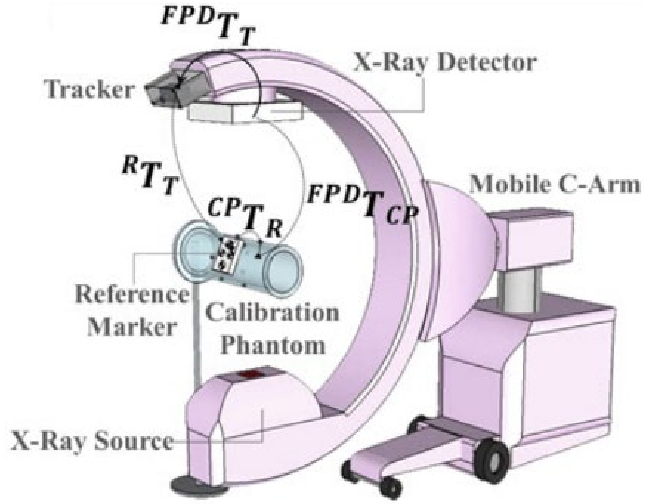




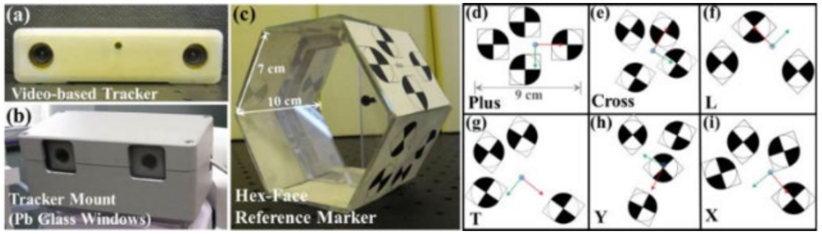
[2]Joerg Traub, Tim Hauke Heibel, Philipp Dressel, Sandro Michael Heining, Rainer Graumann, and Nassir Navab, "A multi-view Opto-Xray imaging system: development and first application in trauma surgery", In *Proceedings of the 10th international conference on Medical image computing and computer-assisted intervention* (MICCAI) , 2007

State of the Art: RGB Camera (2D) to CBCT (3D)

- Tacker-on-C[3]
  - Rigidly mounted a tracker on C-arm
  - Hex-faces reference markers
  - Calibration between tracker and detector plane (one-time)
  - Intra-operative paired-point registration (marker to CBCT)
  - Live tracking provide overlaid of video and DRR of CBCT
  - Accuracy of 0.87±0.25 mm



✓ Pros
  - **More accurate tracking** than in-room tracker
  - **Live visual feedback in the view of tracker**
  - Reduced number of x-rays



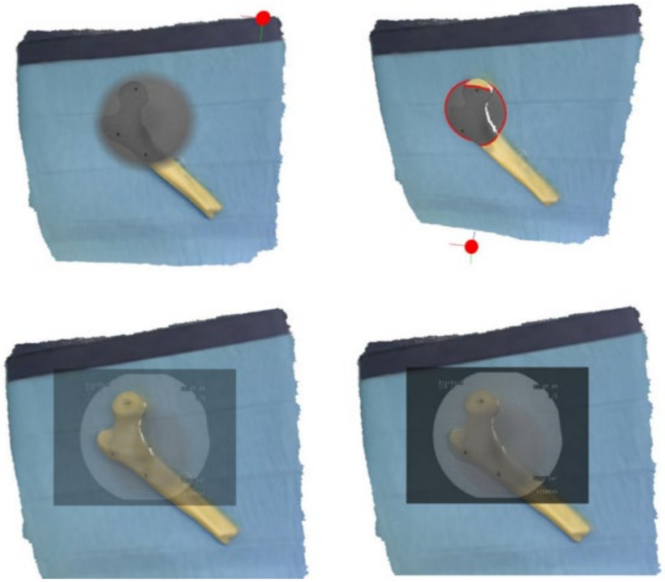
✗ Cons
  - **Involved intra-operative setup**
  - Visual markers used ➔ line-of-sight problem
  - **Moving of C-arm to provide different views**

[3]Reaungamornrat, S.; Otake, Y.; Uneri, A.; Schafer, S.; Mirota, D.J.; Nithiananthan, S.; Stayman, J.W.; Kleinszig, G.; Khanna, A.J.; Taylor, R.H.; Siewerdsen, J.H., "An on-board surgical tracking and video augmentation system for C-arm image guidance," in *International Journal of Computer Assisted Radiology and Surgery (IJCAR), 2012*

State of the Art: RGBD Camera (3D) to X-Ray (2D) (1)

- RGBDX[4]
  - CAMC with replacement of RGB by RGBD
  - Surface reconstruction from depth camera
  - Live overlay of X-ray and 3D surface
  - Projection error 0.71-3.14 mm (3 models)
  - Studied if mirror has effect on depth camera

✓ Pros
  - Simple and one-time calibration
  - Live visual feedback overlaid on X-ray
  - Reduced number of X-rays
  - **Improved depth perception from the 3D surface**

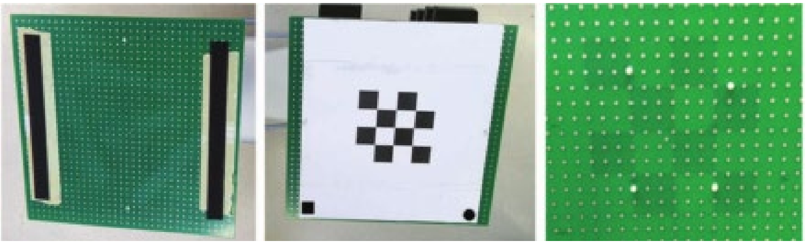


✗ Cons
  - Upside down design and reduced working space
  - 2D X-ray does not provide enough depth information
  - **Physically correct only at the view of X-ray**
  - Requires new X-ray when C-arm is moved

[4] S. Habert, J. Gardiazabal, P. Fallavollita, N. Navab. RGBDX: first design and experimental validation of a mirror-based RGBD Xray imaging system International Symposium on Mixed and Augmented Reality (ISMAR), 2015

State of the Art: RGBD Camera (3D) to X-Ray (2D) (2)

- RGBD/C-arm Calibration[5]
  - RGBD camera rigidly mounted on C-arm without mirror!
  - Calibration board with grid pattern
  - 3D to 2D projection matrix estimation by DLT and Levenberg-Marquardt algorithm
  - 3D from depth camera, 2D from distorted X-ray
  - Accuracy of 0.54±1.40 mm



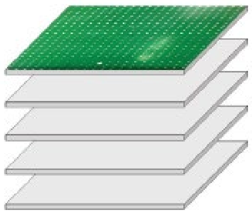
✓ Pros
  - Simple and one-time calibration
  - Live visual feedback on top of X-ray
  - Reduced number of X-rays
  - **Improved depth perception from the 3D surface model**
  - **No mirrors: more work space**

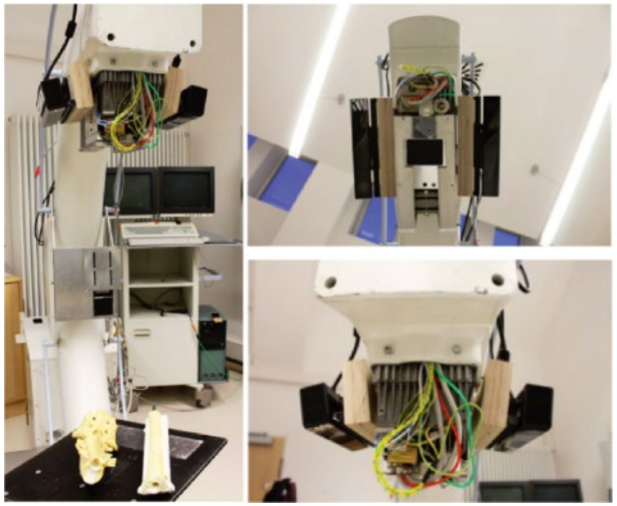
✗ Cons
  - Not enough depth information from 2D X-ray
  - **Physically correct only at the view of X-ray**
  - Requires new x-ray when C-arm is moved

[5] Wang, X., Habert, S., Meng, M., Wang, X., Huang, C.H., Fallavollita, P., Navab, N., “Rgb-d/c-arm calibration and application in medical augmented reality”, in: International Symposium on Mixed and Augmented Reality (ISMAR), 2015

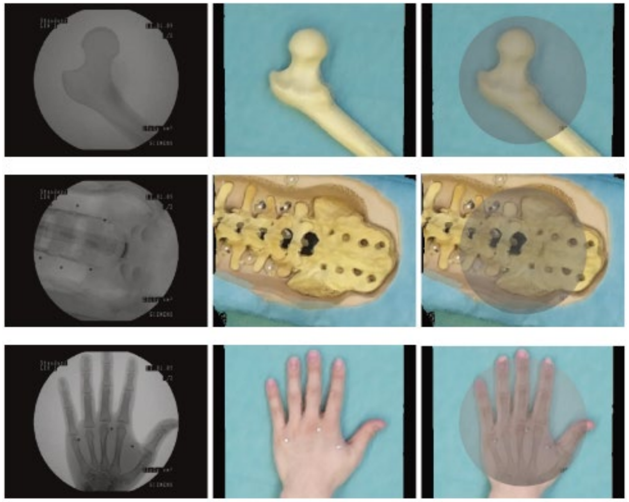
State of the Art: 2 RGBD Cameras (3D) to X-Ray (2D)

- Headphone C-Arm[6]
  - 2 RGBD cameras rigidly mounted on C-arm
  - Calibration board with grid pattern (Tsai's method)
  - 3D stereo camera calibration
  - Overlay error 1.5-2.0 mm





✓ Pros
  - Simple and one-time calibration
  - Live visual feedback on top of X-ray
  - Reduced number of X-rays
  - **Improved depth perception**
  - **No mirrors: more work space**
  - Live surface reconstruction by 2 cameras

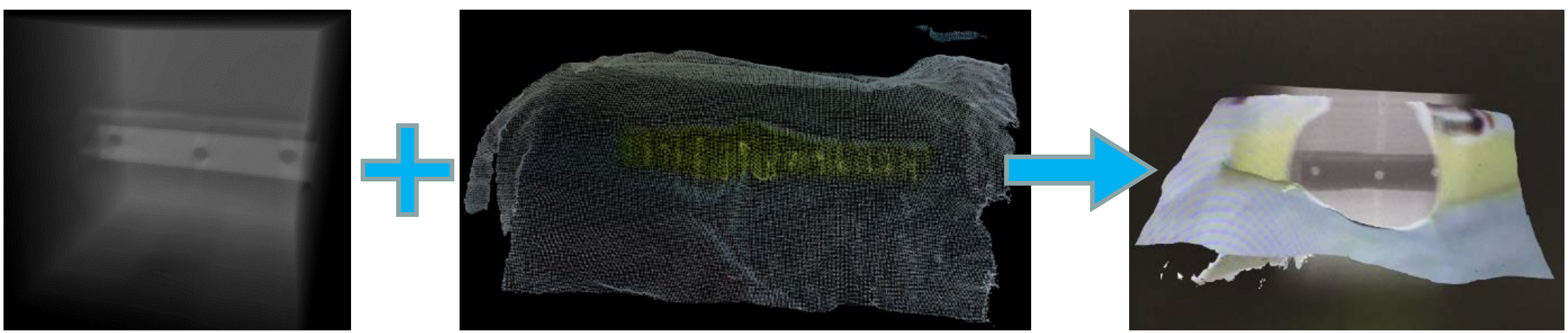


✗ Cons
  - Not enough depth information from 2D X-ray
  - **Physically correct only at the view of X-ray**
  - Requires new x-ray when C-arm is moved

[6] S. Habert, Ma Meng, W. Kehl, Xiang Wang, F. Tombari, P. Fallavollita, N. Navab. Augmenting mobile C-arm fluoroscopes via Stereo-RGBD sensors for multimodal visualization International Symposium on Mixed and Augmented Reality (ISMAR), 2015

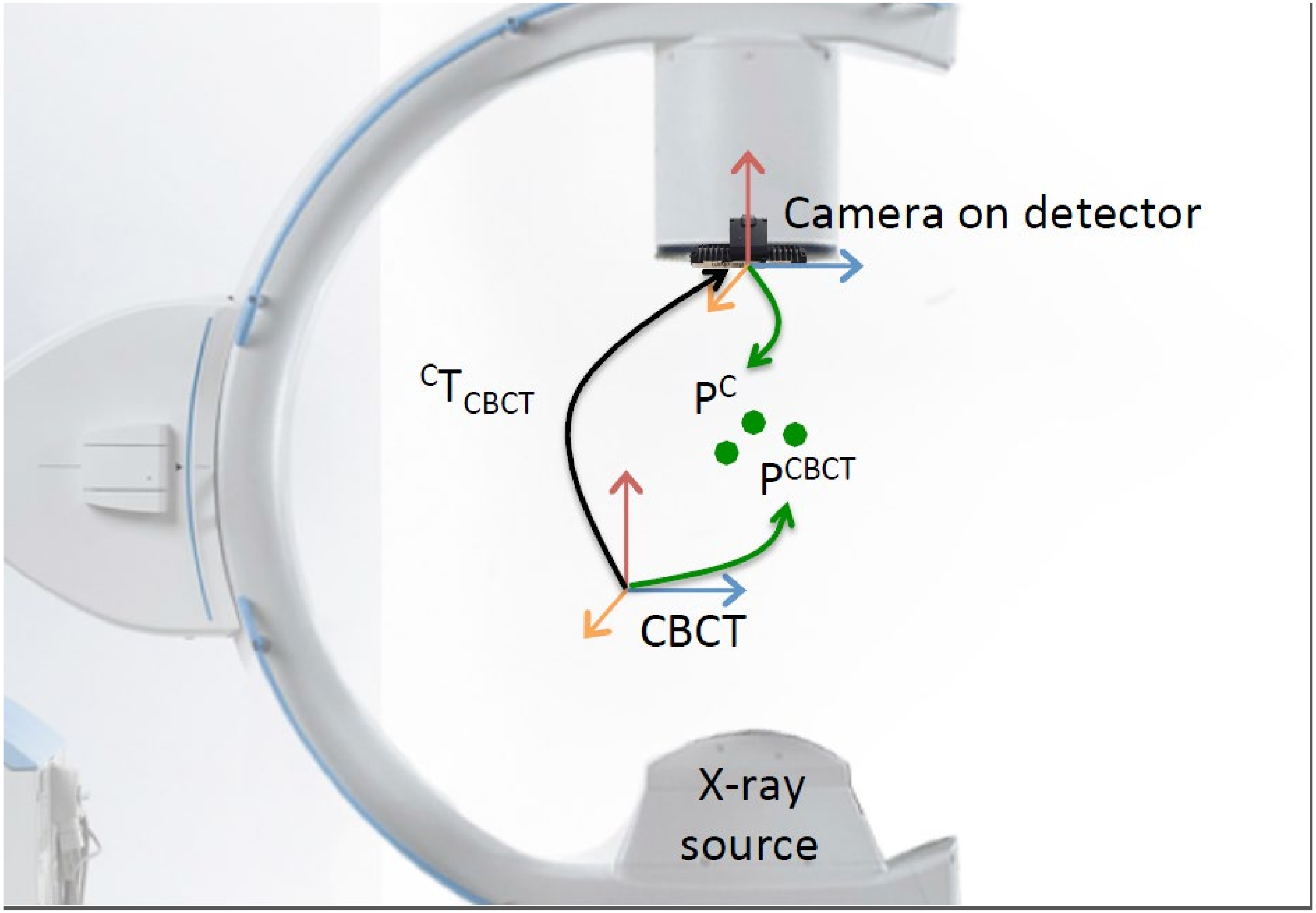
Problem Statement: Technical Development

- Several methods have been proposed: Combining different imaging techniques
  - Camera augmented mobile C-arm
  - Laparoscopic view and CT registration
  - RGBD camera and CT registration
- Objective: 3D RGBD Camera and 3D CBCT Volume Calibration
  - Tackle the problem by integrating an RGBD camera into C-arm
  - Calibrate the RGBD camera and CBCT volume
  - Hence, provide direct 3D-3D overlay visualization

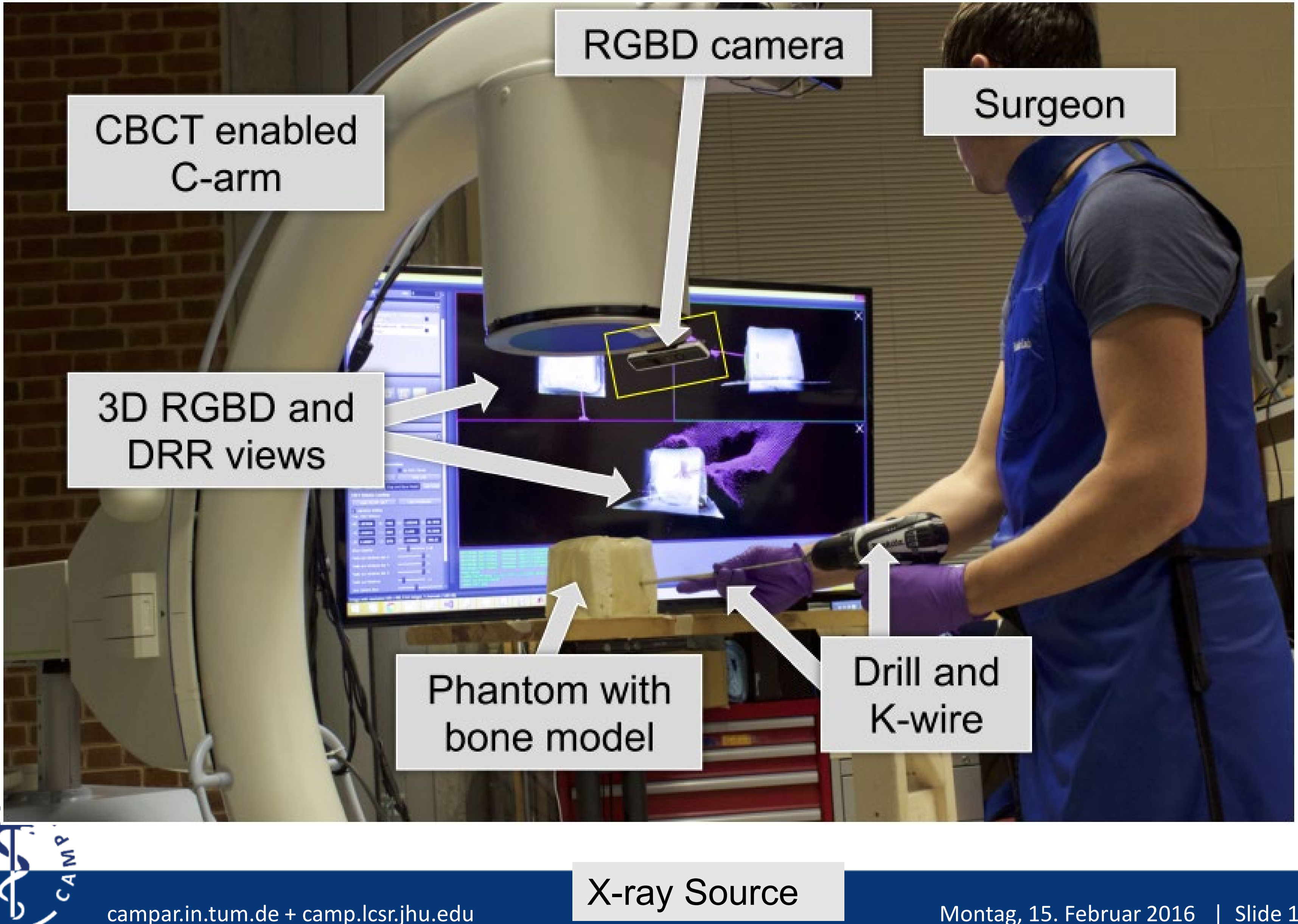


DRR Surface Overlays

System Setup and Coordinate Centers for Calibration



System Setup: pre-clinical usability study

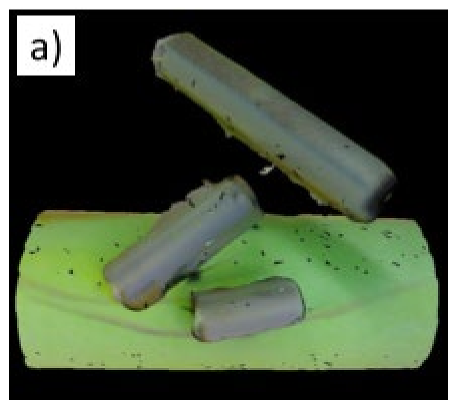


Calibration Method: Phantom Design

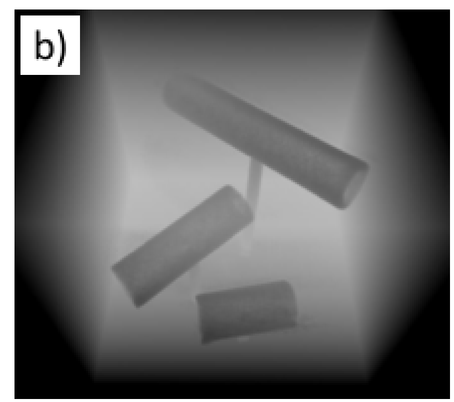
- RGBD camera rigidly mounted on the C-arm detector!
  ➔ rigid transformation between RGBD camera and CBCT ($^{c}T_{CBCT}$)

- Calibration Phantom:
  - Visible in both depth camera and CBCT
  - Three pipes with higher radio absorption
  - Round surfaces
  - Arranged in different heights, lengths and orientations

Calibration Phantom



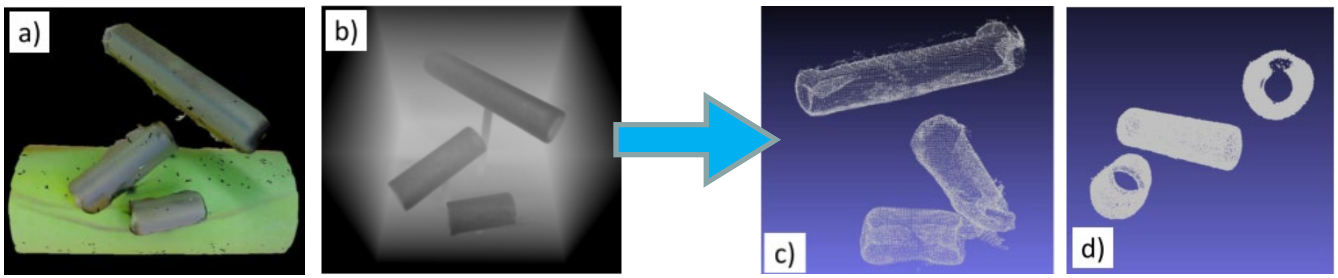
Surface Reconstruction



CBCT

Calibration Method: Data Extraction and Initialization

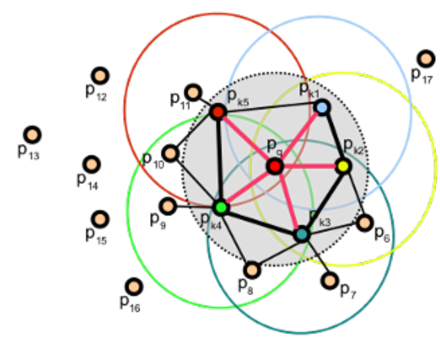
- Data Extraction:
  - Acquire CBCT and the surface reconstruction simultaneously
  - Extract the surface from CBCT and extract the point clouds of the calibration phantom*
  - Extract the points clouds of the calibration phantom from the surface reconstruction



- Registration Initialization
  - Fast Point Feature Histograms (FPFH) and Sample Consensus Initial Alignment (SAC-IA) for initialization[7]

$$FPFH_i^S = PFH_i^S + \frac{1}{k}\sum_{j\in\Omega_i}\frac{1}{\omega_j}PFH_j^S$$

  - where *PFH* is the Point Feature Histogram, which collects angular variations of point clouds as features
  - Fast, robust to outliers / noise and provided in PCL[8]



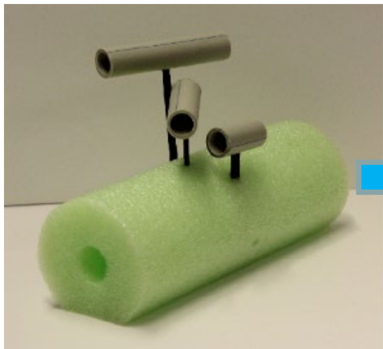
*ImFusion SDK

[7]Rusu, R., Blodow, N., Beetz, M., "Fast point feature histograms (fpfh) for 3d registration". In: Robotics and Automation, 2009. ICRA '09. IEEE International Conference on, pp. 3212{3217 (2009).

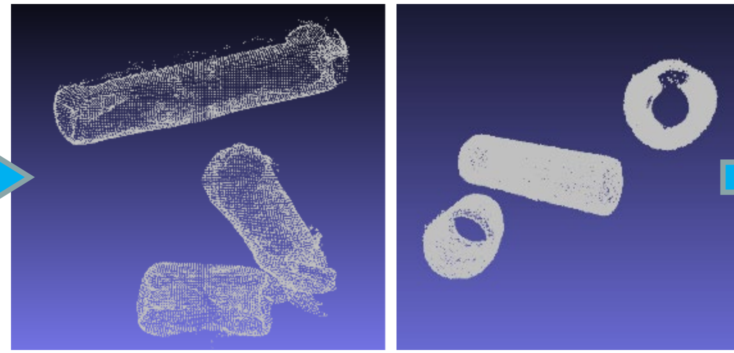
[8]Rusu, R.B., Cousins, S.: 3d is here: Point cloud library (pcl). In: Robotics and Automation (ICRA), 2011 IEEE International Conference on, pp. 1{4. IEEE (2011)

Calibration Method: Registration

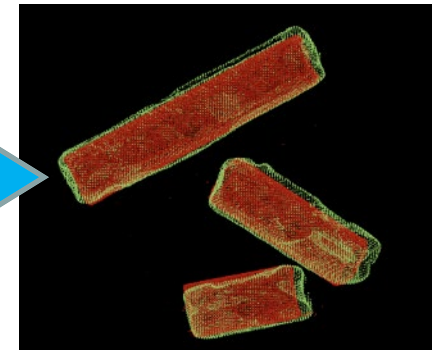
- Iterative Closest Points (ICP) is then used to refine the registration result



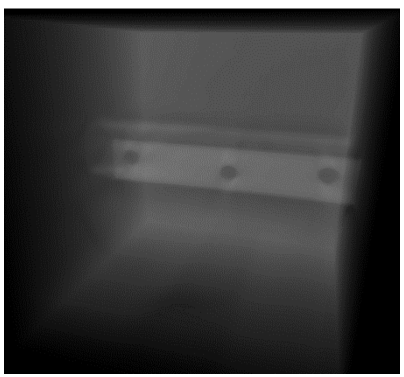
Calibration Phantom



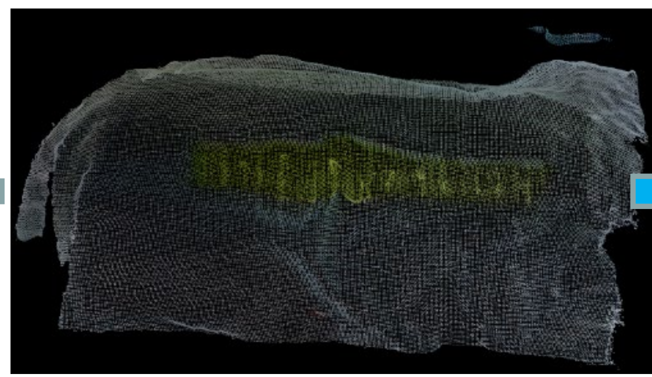
Point Clouds in both modalities



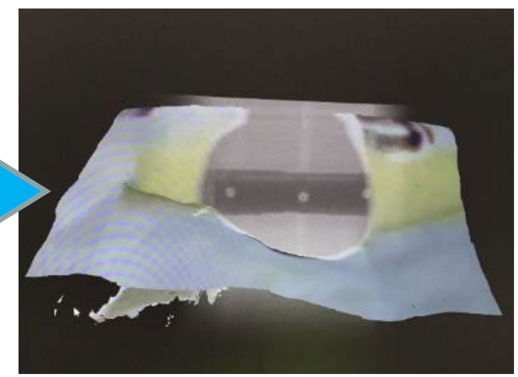
Registered Point Clouds



DRR



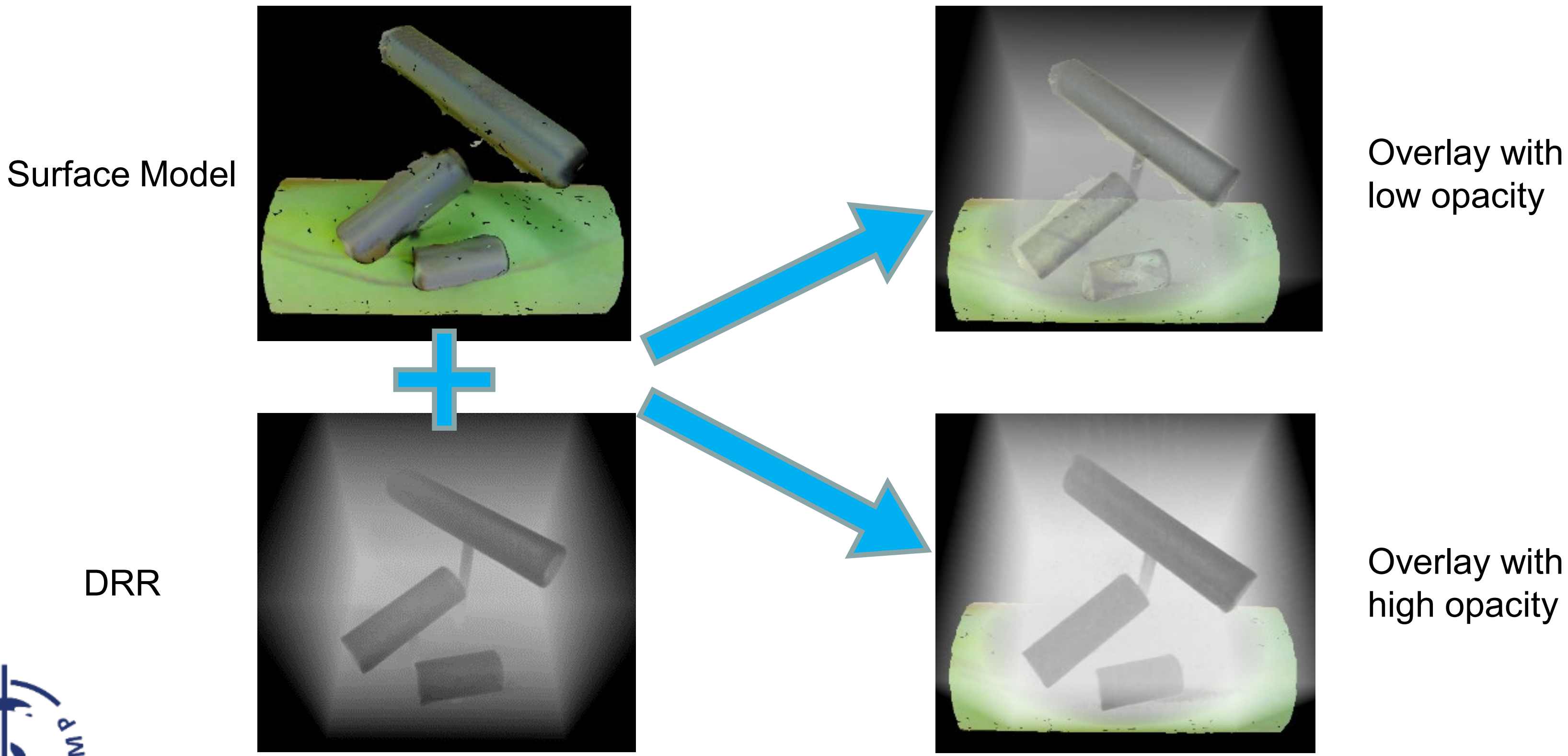
Surface



Overlays

Intra-operative Mixed Reality Visualization

- Steps:
  - Acquire CBCT and the surface reconstruction simultaneously
  - Simulate X-ray from CBCT using DRR
  - Apply calibration result to overlay DRR onto surface
  - Provide semitransparent views from any arbitrary angles



Results – Repeatability

- Repeat the calibration five times with different orientations
  - The test shows small variation (shown in standard deviation)

Error	α (rad)	β (rad)	γ (rad)	x (mm)	y (mm)	z (mm)	$\|{}^{c}\mathbf{t}_{CBCT}\|_2$
F200	0.0045	0.0059	0.016	0.89	0.29	0.81	0.84
Kinect	0.0047	0.0027	0.0079	0.31	0.74	0.35	0.46

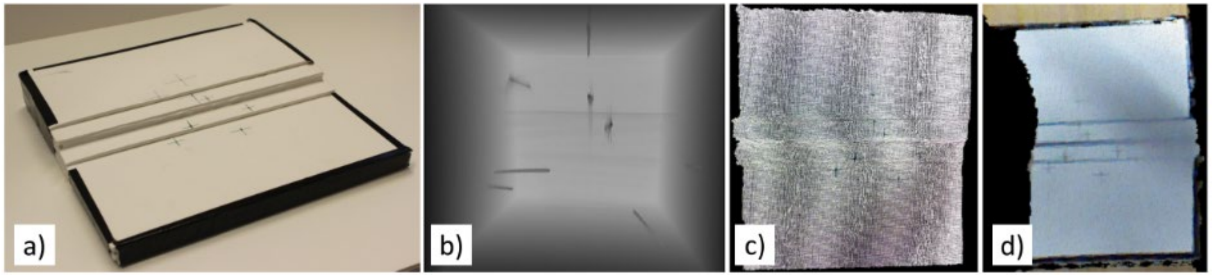
- Also tested the method with point clouds densities
  - The test also shows small variation with different densities
  - However, FPFH failed if too less points

Grid Size (mm)	# of pts (CBCT)	# of pts (Depth)	α (rad)	β (rad)	γ (rad)	x (mm)	y (mm)	z (mm)
0.5	51831	21014	0.020	0.0025	0.014	0.22	0.23	0.56
1.0	18684	16221	0.0079	0.0018	0.0027	0.47	0.55	0.29
1.5	9016	8536	0.0018	0.0015	0.0041	0.33	0.25	0.57
2.0	5238	5183	0.0014	0.0025	0.0038	0.48	0.18	0.16

- Resistance to outliers / noise provided by FPFH and ICP

Results – Accuracy

- Phantom designed to measure the Target Registration Error (TRE)
  - The visual and radio-opaque landmarks are non-linear, non-coplanar, and non-uniformly distrusted around the center



Test Phantom | DRR | Pts in Intel | Pts in Kinect

TRE 1	δx	δy	δz	$\|\delta\|_2$
F200	1.26 ± 0.73	1.94 ± 1.50	0.98 ± 0.95	2.91 ± 1.10
Kinect	0.58 ± 0.56	2.87 ± 1.97	5.61 ± 1.72	6.54 ± 2.04

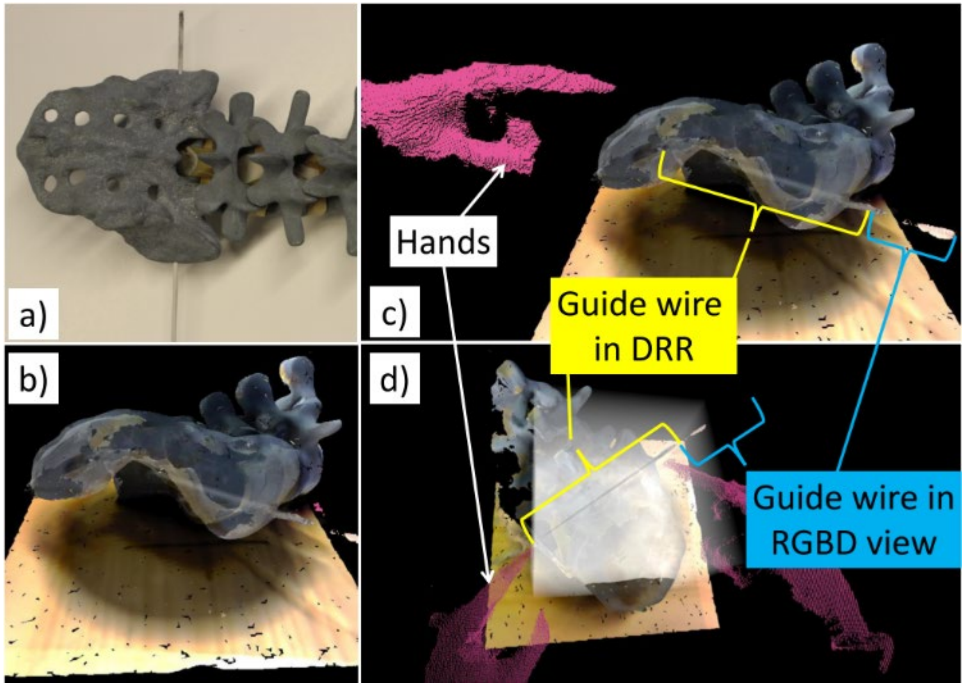
TRE 2	δx	δy	δz	$\|\delta\|_2$
F200	0.72 ± 0.78	2.46 ± 1.12	1.12 ± 0.87	2.91 ± 1.37
Kinect	1.09 ± 0.49	3.19 ± 0.83	7.30 ± 1.19	8.11 ± 1.02

TRE 3	δx	δy	δz	$\|\delta\|_2$
F200	0.83 ± 0.57	0.72 ± 0.52	1.40 ± 1.00	1.92 ± 0.98
Kinect	1.40 ± 0.65	1.97 ± 1.33	7.11 ± 1.33	7.60 ± 1.55

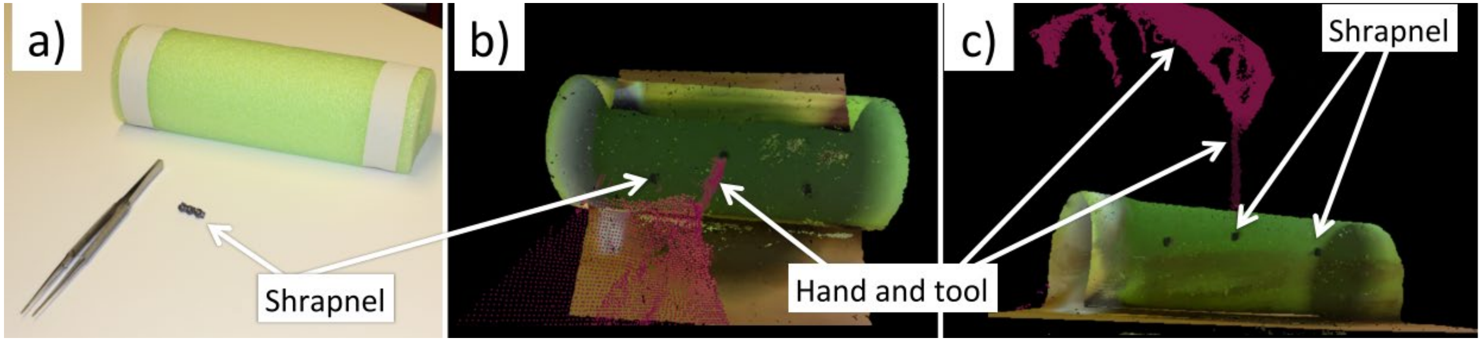
- Average accuracy of 2.58 mm (Intel) and 7.42 mm (Kinect)

Clinical Applications

- Features:
  - Mixed reality visualization
  - Live moving point clouds
  - Multiple desired views from arbitrary angles

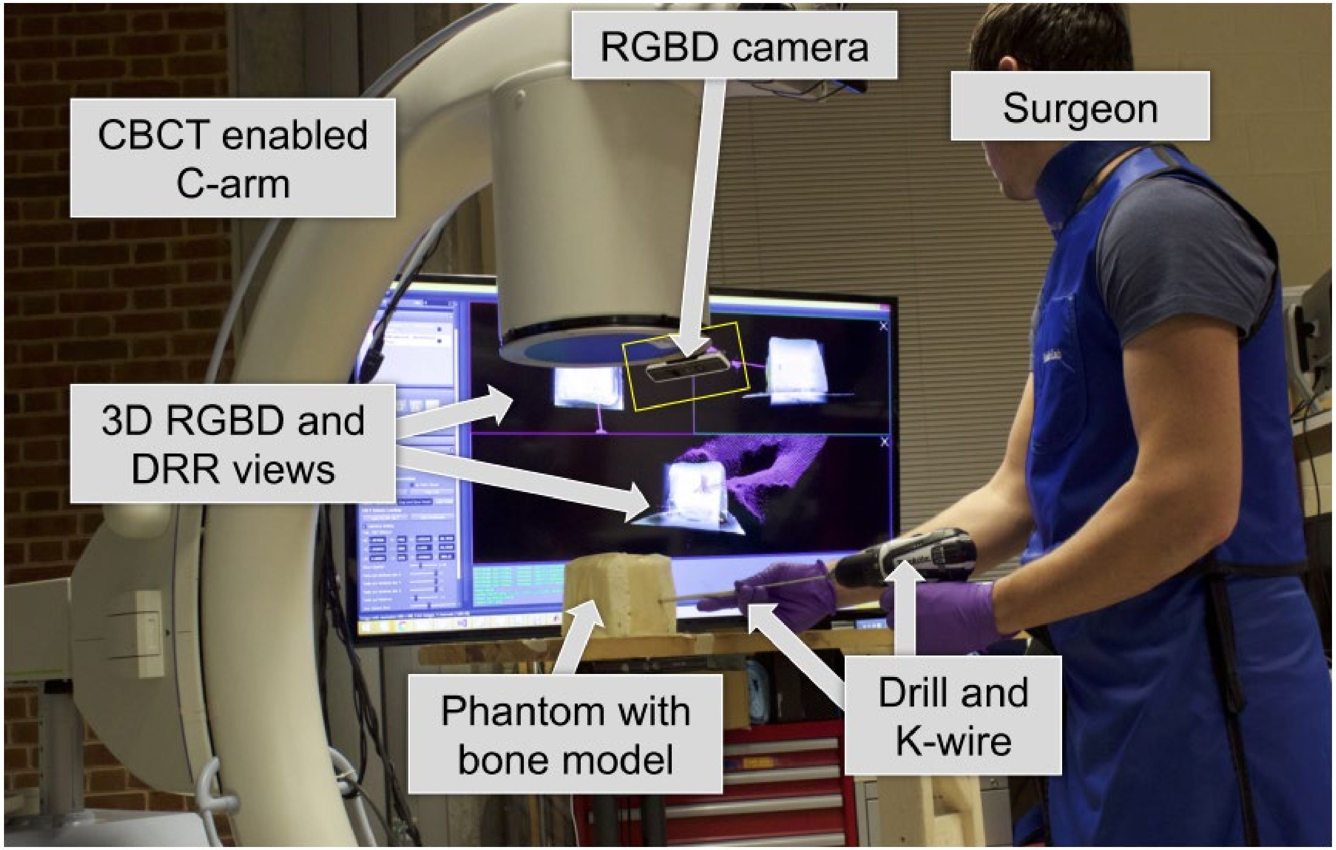


- Applications:
  - K-wire placement
  - Shrapnel removal
  - Etc …



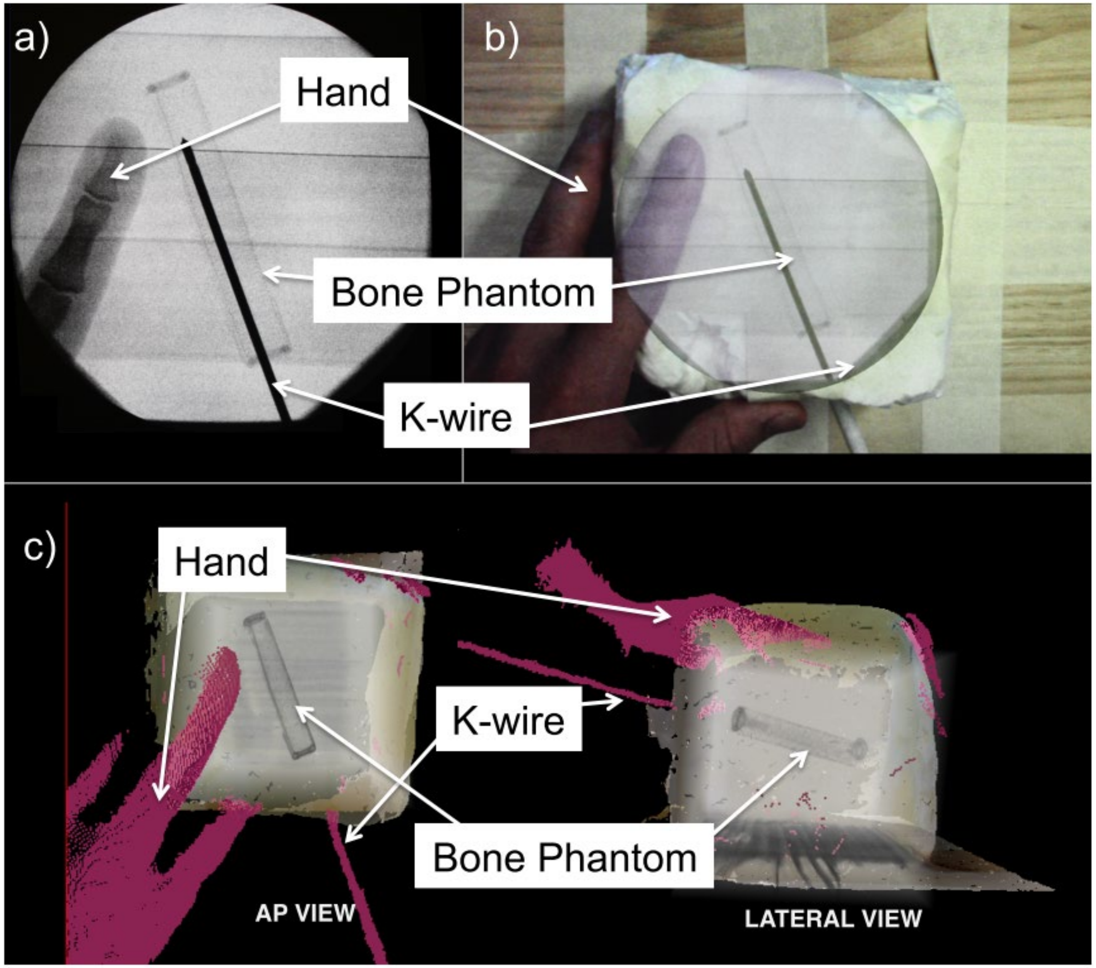
Pre-clinical Usability Study

- 7 surgeons invited to Mock OR at JHU, Baltimore
- Perform simulated task with 3 different methods (X-Ray, CAMC and ours)

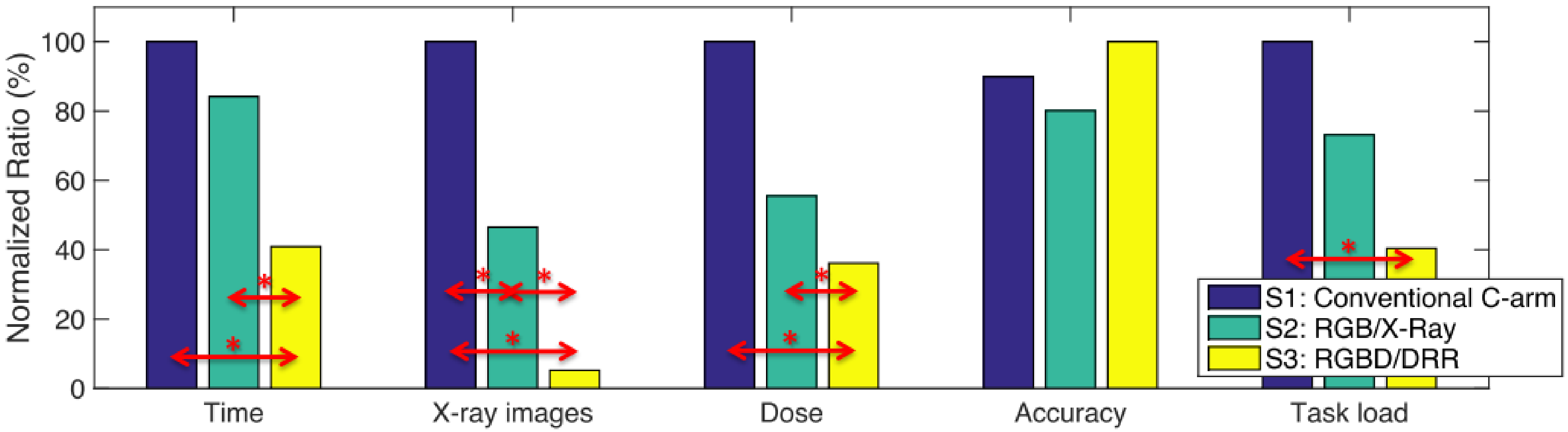


Evaluation Task and Measurement

- Place a K-wire into a tube
- Measurement:
  - Time taken
  - Number of X-rays
  - Total radiation dose
  - Placement accuracy
- Questionnaire:
  - Surgical Task load
  - Feedback



Evaluation Results

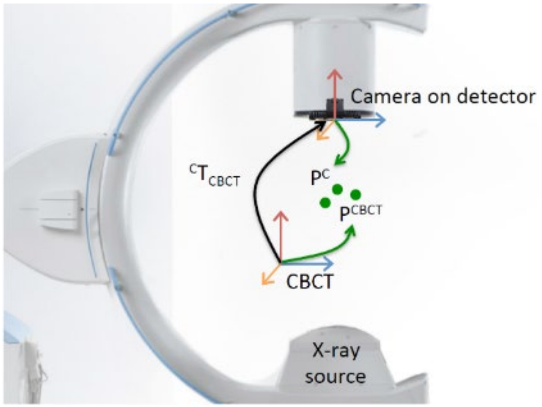


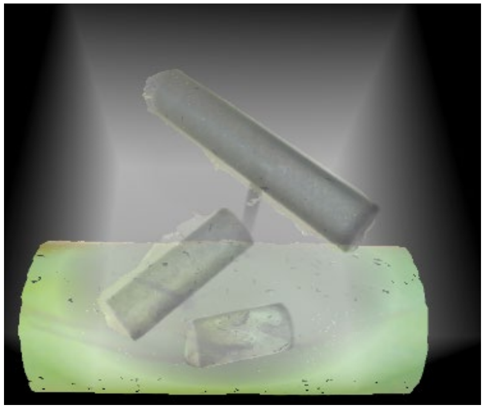
	S1: C-Arm	S2: RGB/X-ray	S3: RGBD/DRR
Time (sec)	594 ±188	500 ±172	243 ±84
X-ray images	40.86 ±19.38	19.00 ±5.72	2.14 ±0.69
Dose ($cGycm^2$)	4.43 ±2.00	2.46 ±1.50	1.60 ±0.17
Error (mm)	4.61 ±3.62	4.11 ±1.97	5.13 ±2.72
Task Load	43.48 ±24.03	31.81 ±20.76	17.57 ±9.33

- It concluded that new system has clear advantages over the conventional

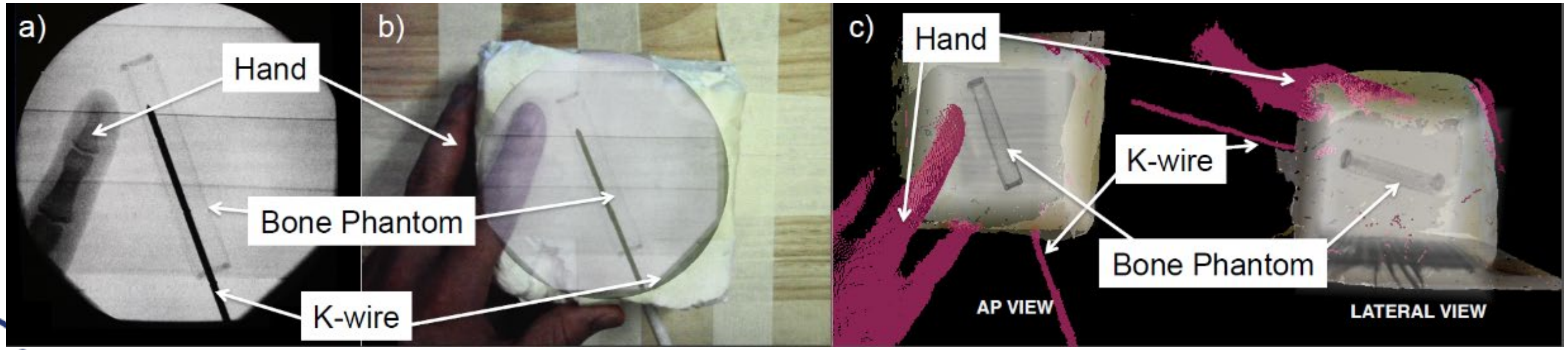
Conditionally Accepted by IPCAI 2016

- *S.C. Lee, B. Fuerst, J. Fotouhi, M. Fischer, G. Osgood, N. Navab,* "Calibration of RGBD Camera and Cone-Beam CT for 3D Intra-operative Mixed Reality Visualization "





- *M. Fischer, B. Fuerst, S.C. Lee, J. Fotouhi, S. Habert, S. Weidert, E. Euler, G. Osgood, N. Navab,* "Pre-Clinical Usability Study of Multiple Augmented Reality Concepts for K-Wire Placement

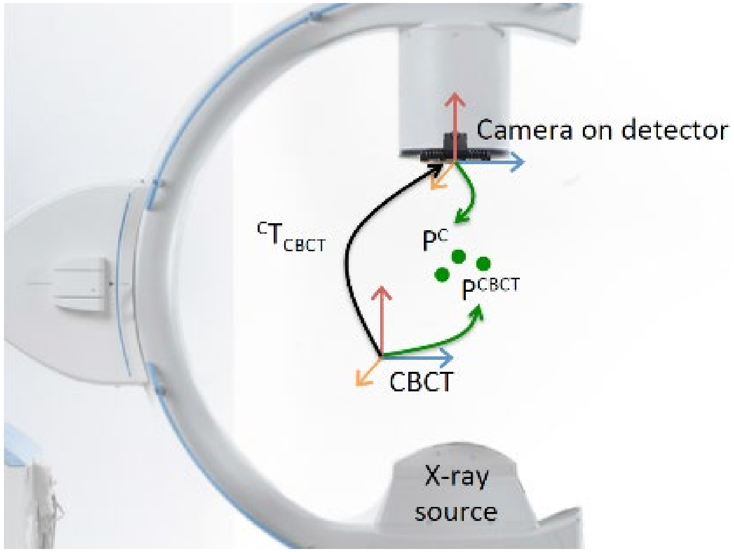


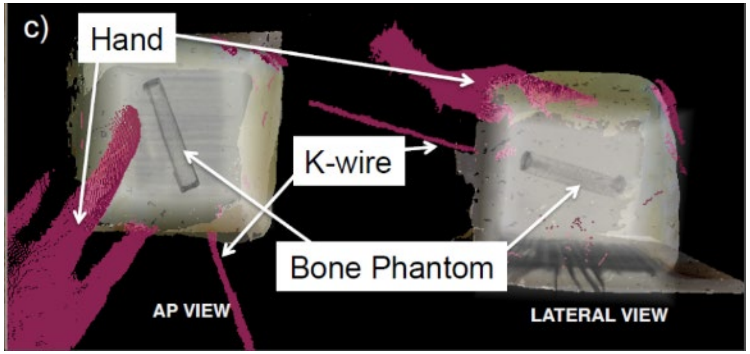
Discussion and Future Work

- RGBD Mixed Reality Visualization
  - Rigidly mounted an RGBD camera on C-arm detector
  - 3D point clouds registration (FPFH and ICP)
  - Multiple views of surface and DRR overlays
  - Live point clouds feedback

✓ Pros
  - Simple and one-time setup calibration
  - Multiple desired views for better depth perception
  - Reduced number of x-rays
  - Reduced operating time

✗ Cons
  - Overlay is invalid when C-arm is moved
  - Accuracy of 2.58 mm (> 2mm)
  - Poor surface visualization





Acknowledgement

- Prof. Nassir Navab, Bernhard Fuerst, Javad Fotouhi, Marius Fischer and all my friends who help and support me, including but limited to: Risto, Carson, Michael, Jennifer, Rob, Daniil, Nikita, Iskandar, Ayushi, Subhransu, Shahriar, Alex, etc…
- ImFusion GmbH and PCL

Thank you for your attention!

Demo Video