



# Modeling Kinematics of Mobile C-arm and Operating Table as an Integrated Six Degrees of Freedom Imaging System

*Lejing Wang<sup>1</sup>, Rui Zou<sup>1</sup>, Simon Weidert (M.D.)<sup>2</sup>, Juergen Landes (M.D.)<sup>2</sup>, Ekkehard Euler (M.D.)<sup>2</sup>, Darius Burschka<sup>3</sup>, and Nassir Navab<sup>1</sup>*

<sup>1</sup> Chair for Computer Aided Medical Procedures (CAMP). TU Munich. Germany

<sup>2</sup> Trauma Surgery Department. Klinikum Innenstadt. LMU Munich. Germany

<sup>3</sup> Chair for Robotics and Embedded Systems, TU Munich, Germany

Presented by *Lejing Wang*

---

## Positioning Mobile C-arm

- Maneuvering mobile C-arms into the best viewing position in regard to the anatomy, is a routine surgical task
  - C-arm repositioning
  - Down-beam C-arm positioning<sup>1</sup>
- For advanced X-ray imaging techniques
  - Parallax-free X-ray stitching<sup>2</sup>
  - Cone-beam CT<sup>3</sup>
- It generally requires
  - Experiences
  - Time
  - Many X-ray shots



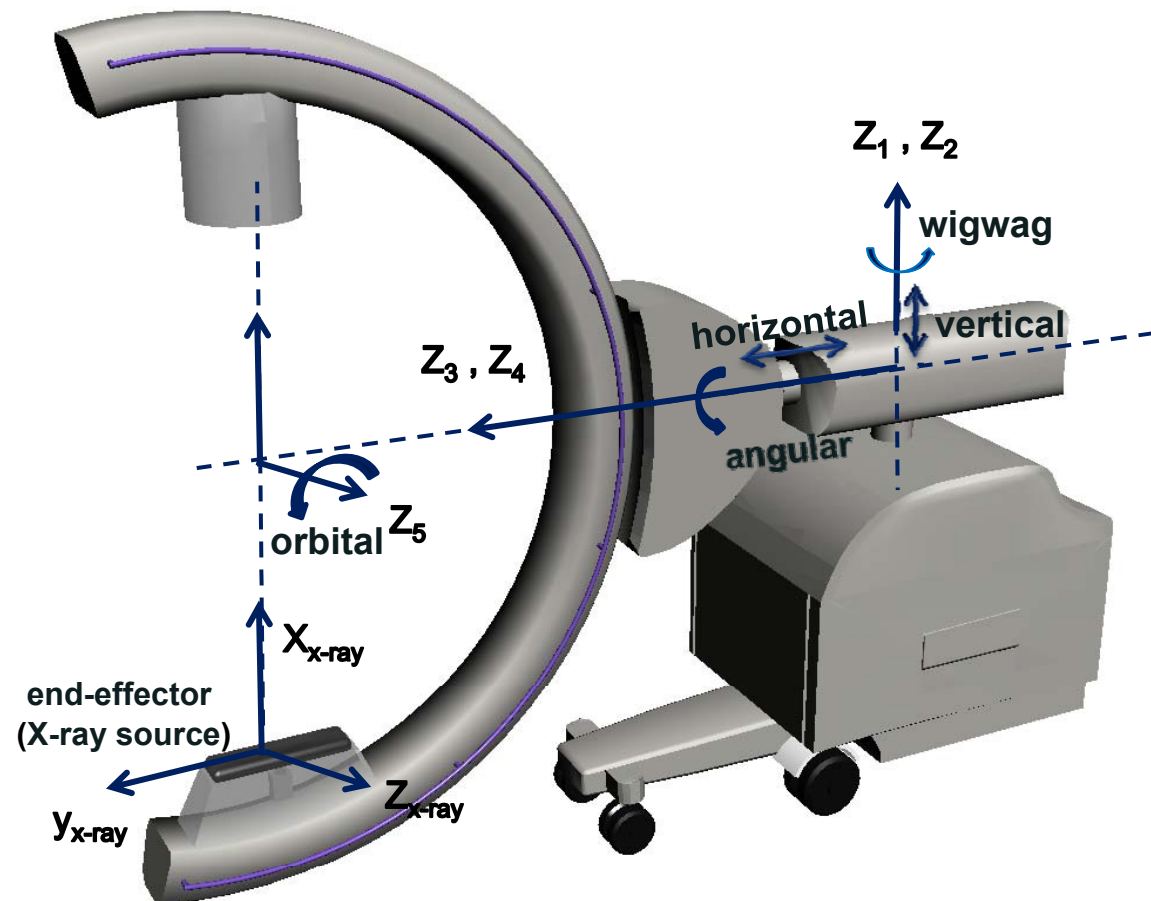
1. Navab et al. MICCAI 06.

2. Wang et al. Medical Image Analysis 2010

3. Matthaus et al. Advanced Robotics 2007

## Standard 5DOF Mobile C-arm

- X-ray source is controlled by a complex kinematic chain of the five joints,
  - **Vertical**, along  $Z_1$
  - **Wigwag**, around  $Z_2$
  - **Horizontal**, along  $Z_3$
  - **Angular**, around  $Z_4$
  - **Orbital**, around  $Z_5$
- Kinematic Analysis for C-arm positioning<sup>1,2</sup>

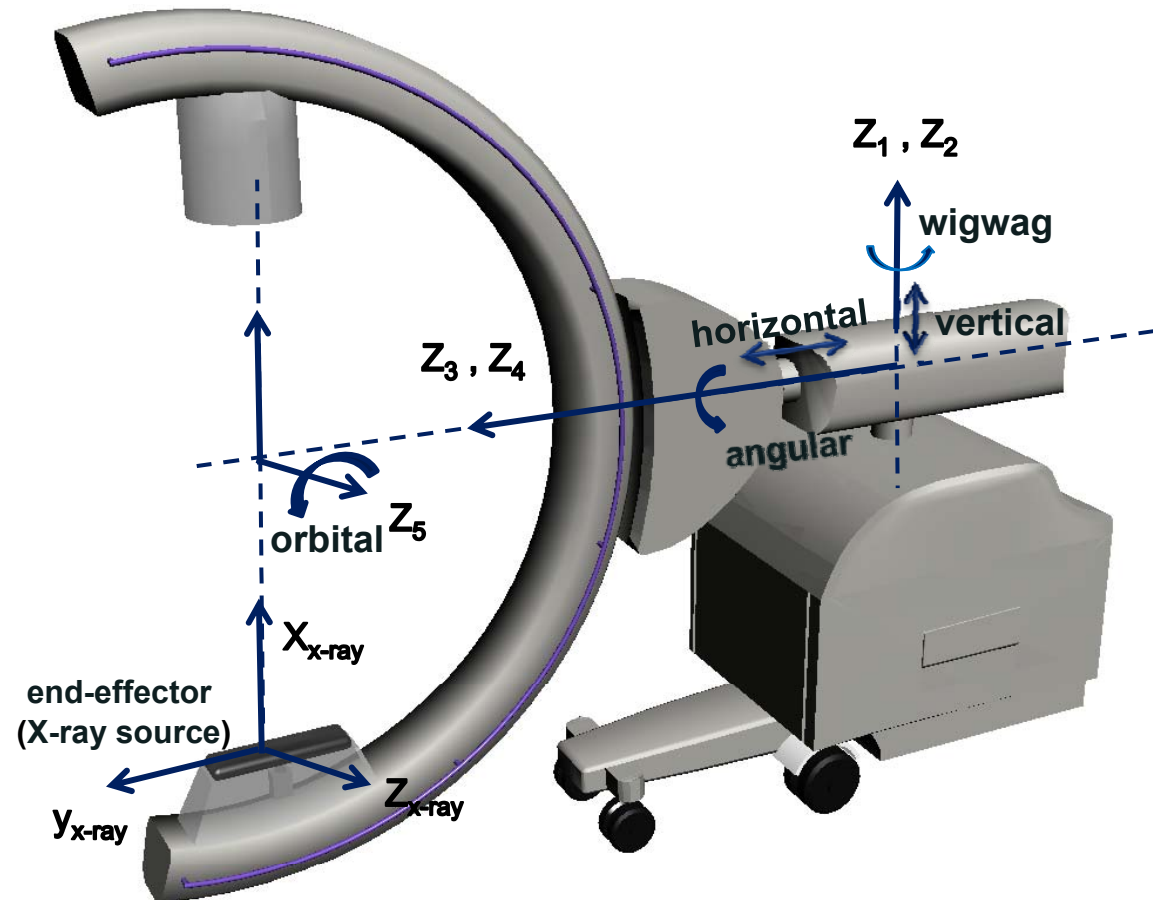


1. Navab et al. MICCAI 06.

2. Matthaus et al. Advanced Robotics 2007


## Limitation of 5DOF


- In 3D Cartesian space, 6 DOF are required for a motion
- X-ray source is certainly restricted in terms of reaching an arbitrary position and orientation





## Related Work

- Reduce the 3D Cartesian space to five DOF <sup>1</sup>
  - rotating X-ray images around the principle point as a missing rotation DOF

the limited DOF could impose some functional constraints, e.g. obstacle avoidance, physical limited joint range, and singularity avoidance
- Parallax-free X-ray image stitching<sup>2 2</sup>
  - moving operating table as an additional DOF to enable a pure rotation of X-ray source relative to the table

It did not include this DOF into the formulation

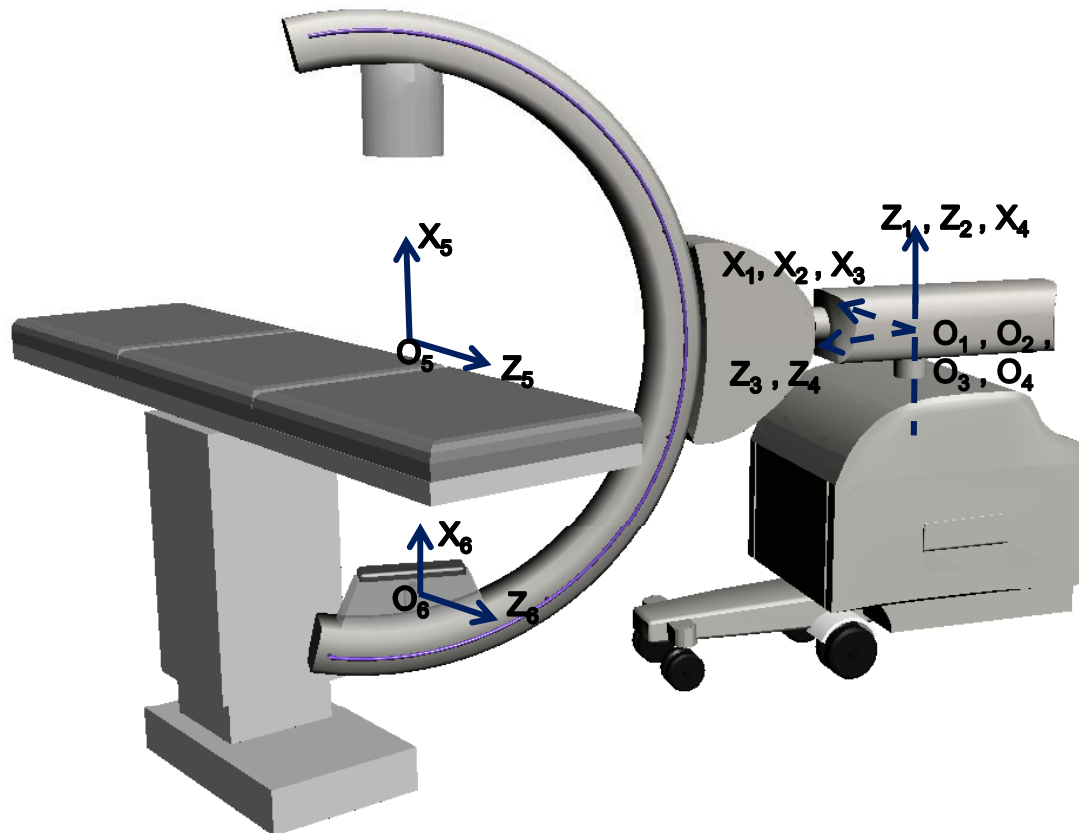
1. Matthaus et al. Advanced Robotics 2007  
2. Wang et al. Medical Image Analysis 2010



## Concept of 6DOF C-arm Modeling

- Integrate a forward-backward translational movement of the patient's table into the 5DOF C-arm's kinematics
  - The X-ray source can be positioned relative to the patient's table with six DOF
-

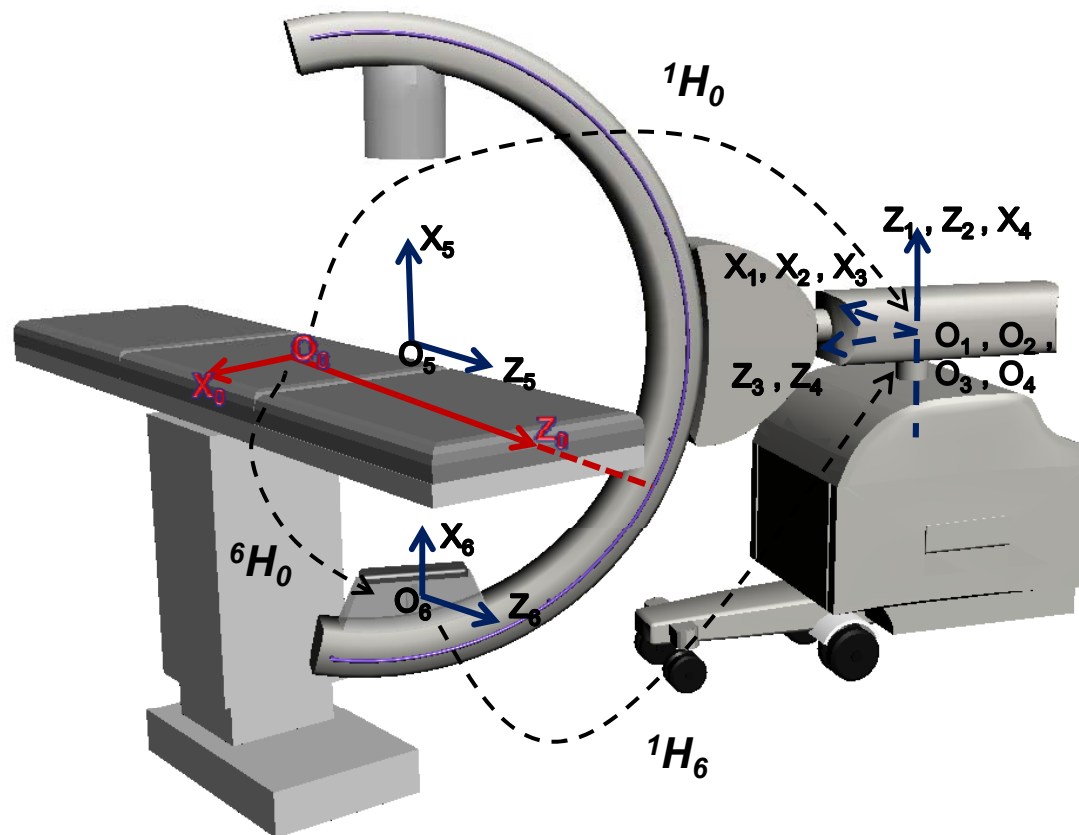
# 5DOF C-arm Kinematic Model



	a (Tx)	d (Tz)	$\alpha$ (Rx)	$\theta$ (Rz)
1	0	$d_1^*$	0	$-\pi/2$
2	0	0	$-\pi/2$	$\theta_2^*$
3	0	$d_3^*$	0	$-\pi/2$
4	0	length_of fset	$\pi/2$	$\theta_4^*$
5	- orbital_off set	0	0	$\theta_5^*$

- Coordinate frames assigned for the 5DOF C-arm according to the Denavit-Hartenberg (DH) rules and its link parameters table (\*variable)

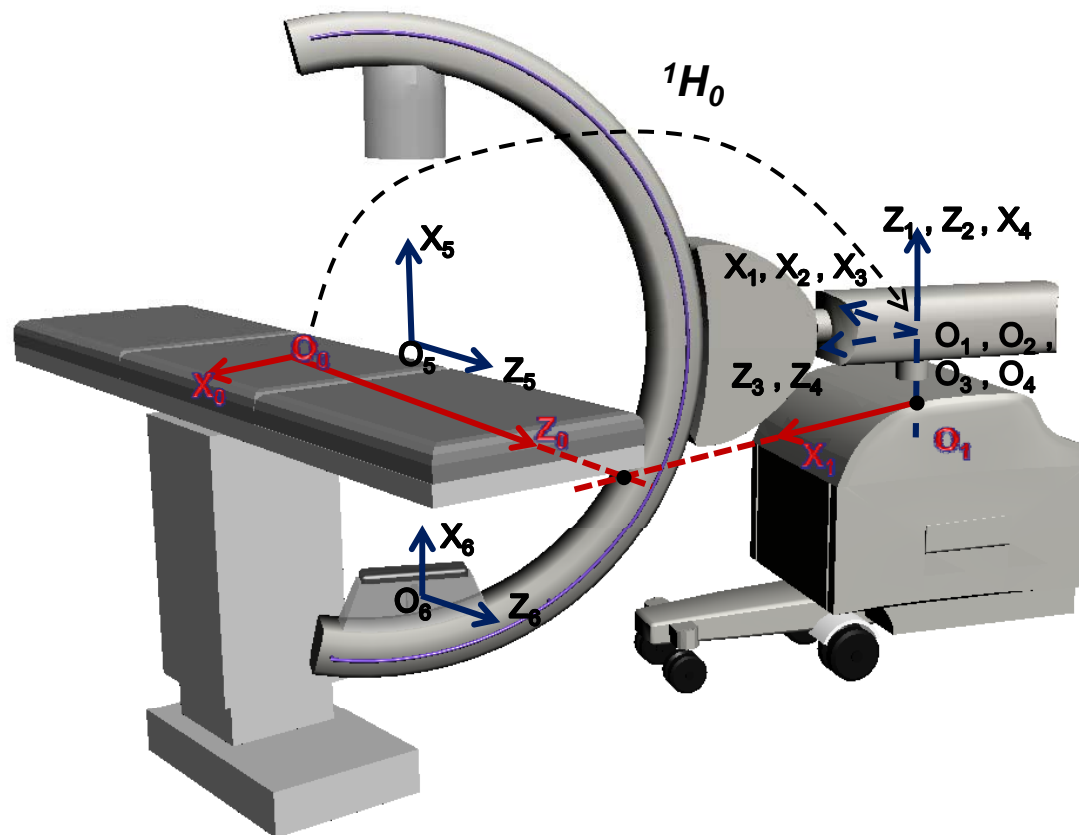
## 6DOF C-arm Kinematic Modeling



- The coordinate frame 0 is assigned to the table
- ${}^6H_0$  from C-arm pose estimation
- ${}^1H_6$  is obtained from the 5DOF C-arm kinematic model
- ${}^1H_0 = {}^1H_6 \cdot {}^6H_0$

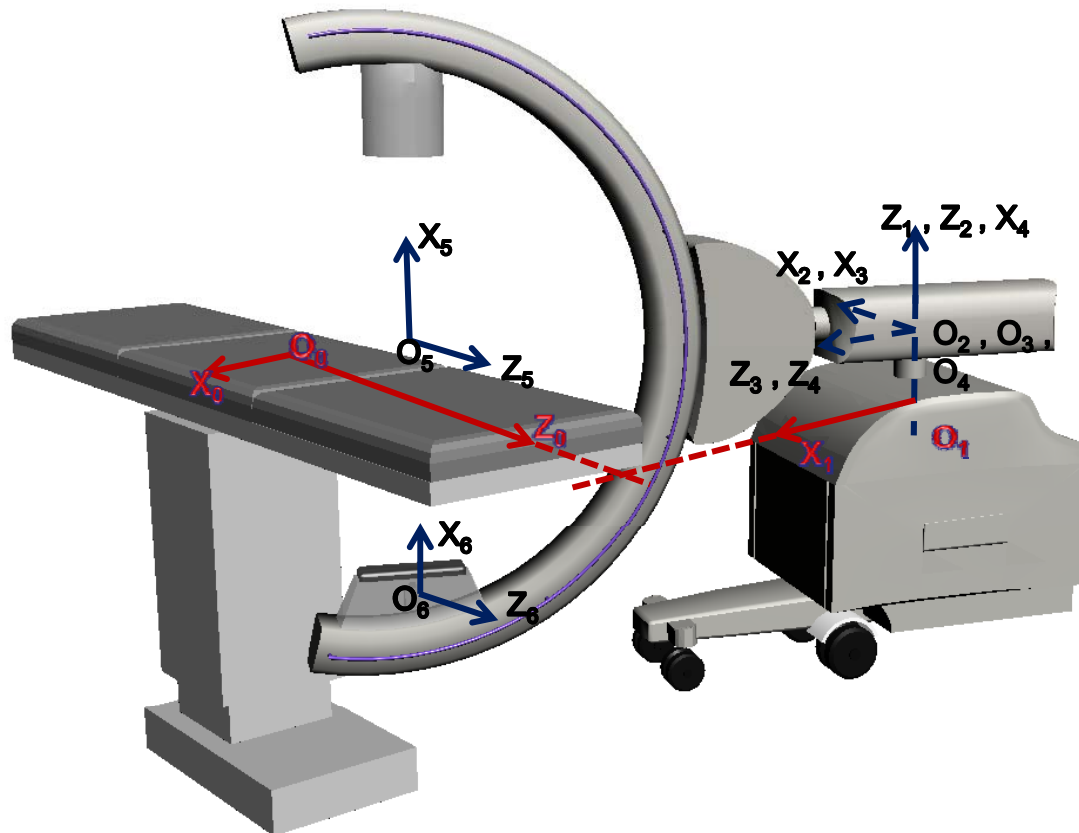


## 6DOF C-arm Kinematic Modeling



- re-assign the coordinate frame 1 in order to satisfy the DH rules
  - $X_1$  should be orthogonal to and intersects with both axes  $Z_0$  and  $Z_1$
- With a known  ${}^1H_0$ , we look for two points on axes  $Z_0$  and  $Z_1$ , which define a minimum distance between them.

# 6DOF C-arm Kinematic Modeling



	a (Tx)	d (Tz)	$\alpha$ (Rx)	$\theta$ (Rz)
0	Dist(Z <sub>0</sub> ,Z <sub>1</sub> )	$d_0^*$ + Dist(X <sub>0</sub> ,X <sub>1</sub> )	Ang(Z <sub>0</sub> ,Z <sub>1</sub> )	Ang(X <sub>0</sub> ,X <sub>1</sub> )
1	0	$d_1^*$ + Dist(X <sub>1</sub> ,X <sub>2</sub> )	0	Ang(X <sub>1</sub> ,X <sub>2</sub> )
2	0	0	-pi/2	$\theta_2^*$
3	0	$d_3^*$	0	-pi/2
4	0	length_of fset	pi/2	$\theta_4^*$
5	- orbital_off set	0	0	$\theta_5^*$

Dist(A,B) – distance between axes A and B;  
 Ang(A,B) – angle between axes A and B;

- Coordinate frames assigned for the 6DOF C-arm according to the Denavit-Hartenberg (DH) rules and its link parameters table (\*variable)



## Controlling of C-arm X-ray Source

- Controlling of the C-arm requires finding the required joint values  $\mathbf{q}$  to position the C-arm X-ray source to a desired pose  $\mathbf{T}$ . --**Inverse Kinematics Problem**.
- Newton iterative method of using pseudo-inverse Jacobian <sup>1</sup>

$$q_{n+1} = q_n + \underset{\substack{\uparrow \\ \text{pseudo inverse}}}{J^+(q_n)} \Delta(F(q_n) - T)$$

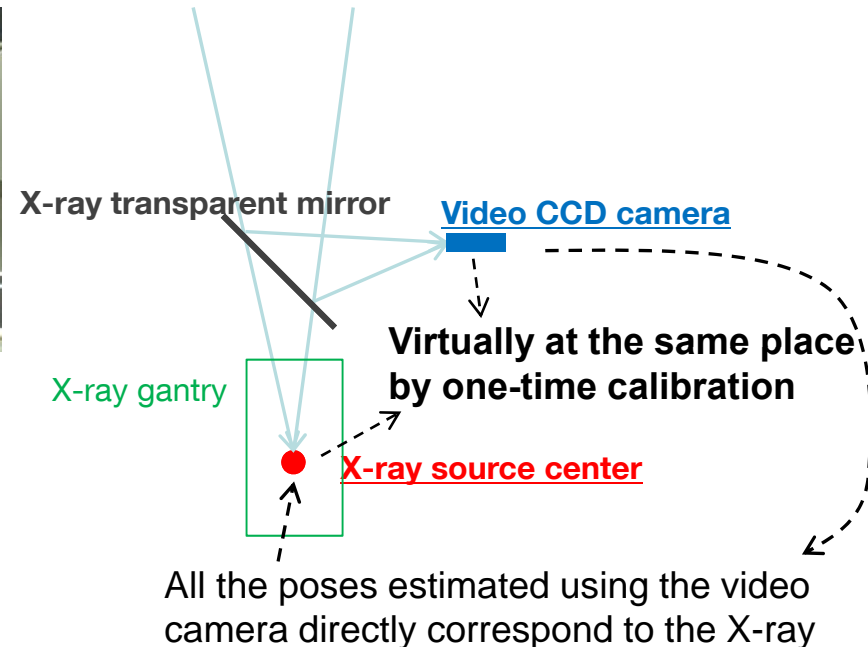
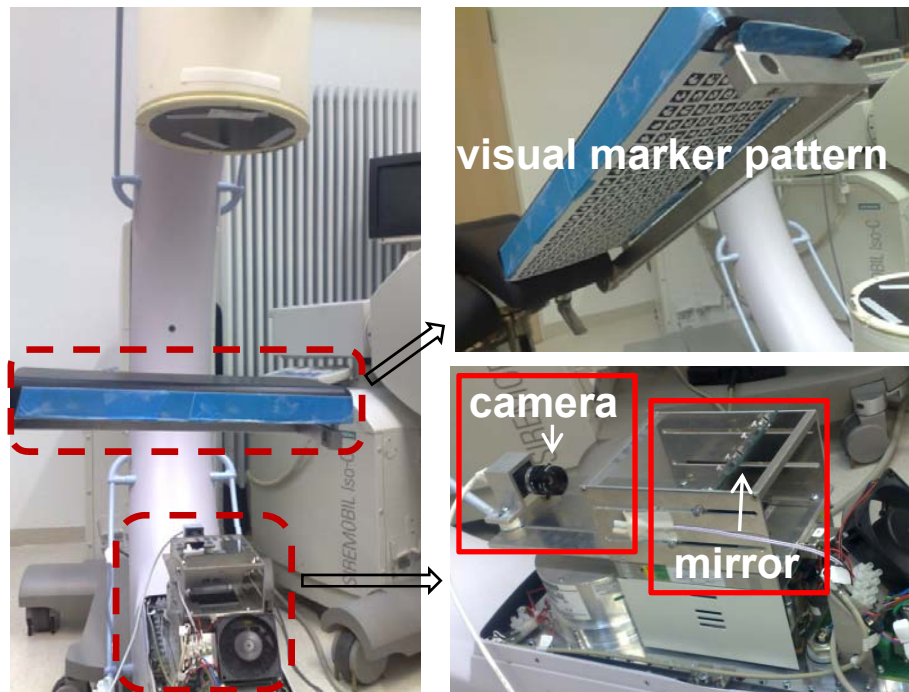
where:

$$T = \begin{bmatrix} n_1 & o_1 & a_1 & p_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{ and } F(q_n) = \begin{bmatrix} n_2 & o_2 & a_2 & p_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\Delta(F(q_n) - T) = \begin{bmatrix} p_1 - p_2 \\ \frac{1}{2}(n_1 \times n_2 + o_1 \times o_2 + a_1 \times a_2) \end{bmatrix}$$

# 6DOF C-arm System Implementation

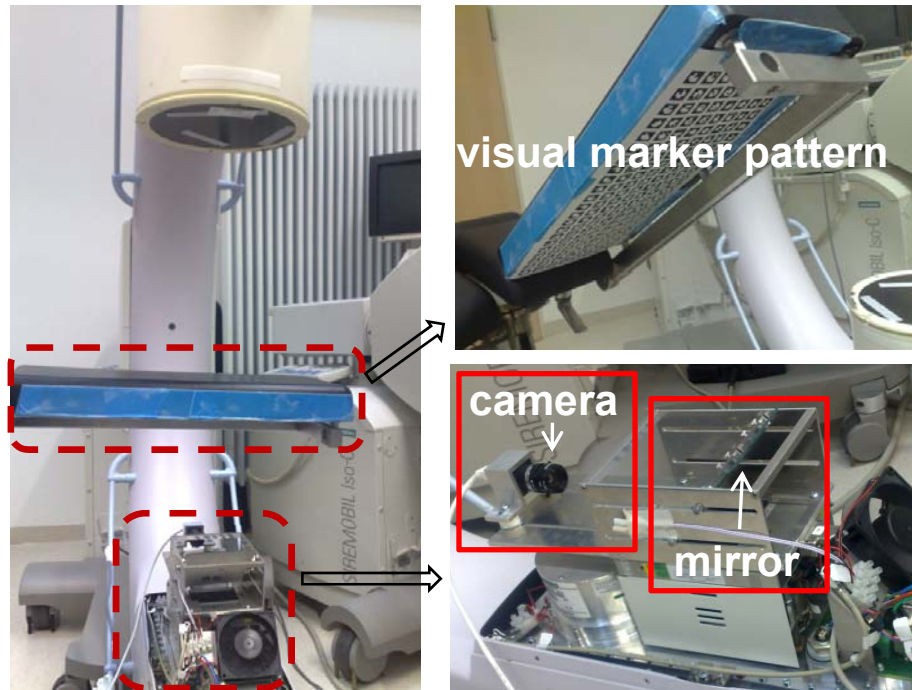
- C-arm pose estimation employs a **Camera Augmented Mobile C-arm (CAMC)** system<sup>1,2</sup> and a **visual marker pattern**



1. Navab et al. IEEE and ACM Int'l Workshop on Augmented Reality, 1999.  
 2. Navab et al.:TMI 2010.

## 6DOF C-arm System Implementation

- C-arm pose estimation employs a **Camera Augmented Mobile C-arm (CAMC)** system<sup>1,2</sup> and a **visual marker pattern**



**no radiation**

- obtaining  ${}^6H_0$  for building 6DOF C-arm model
- Continuous feedback for supporting moving each joint
  - solving inverse kinematics for each estimated C-arm pose

1. Navab et al. IEEE and ACM Int'l Workshop on Augmented Reality, 1999.

2. Navab et al.:TMI 2010.



## C-arm Repositioning Experiment

- During the intervention, the C-arm often has to be moved back to acquire the second X-ray image from the same viewing point as the first one
  - For one repositioning experiment,
    - C-arm was first positioned to a reference pose to acquire a reference X-ray image
    - the operating table was translated and C-arm was moved to a starting pose
    - at the starting pose, 6DOF C-arm kinematic model was built
    - move the C-arm to the pre-defined reference position with continues feedback
-



## Experiment Results

Actual joints	moved	Kinematic model	Computed joint movement values for repositioning: translation(mm), rotation(degree)					Image difference: Mean(pixels)
			table	vertical	wigwag	horizontal	angular	
table, angular	6DOF	102.15	-1.01	-0.13	0.81	5.52	0.32	7.35
	5DOF	non	-1.53	3.45	-1.38	3.89	0.03	70.16
table, wigwag	6DOF	62.07	-0.39	-6.48	-1.00	-0.16	-0.07	5.78
	5DOF	non	-0.45	-4.31	-5.10	-1.16	-0.5	64.40
table, orbital	6DOF	-73.22	-0.49	-0.001	-2.59	-0.06	-9.69	1.38
	5DOF	non	-0.64	-2.70	1.63	1.27	-9.60	59.99
table, horizontal, vertical, angular, orbital, wigwag	6DOF	31.04	43.15	-7.34	39.89	15.40	-16.05	5.18
	5DOF	non	41.70	-6.17	38.58	14.69	-15.41	56.43
vertical, angular, horizontal, orbital, wigwag	6DOF	8.61	42.13	-6.10	67.97	15.12	-7.25	7.41
	5DOF	non	41.84	-5.79	67.98	14.99	-7.33	8.21

- Five pairs of C-arm repositioning.
- Each pair (the same starting and reference positions) consists of two repositioning procedures using 5DOF and 6DOF C-arm model
- Image differences are computed from corners of 4 X-ray square markers



## Discussion and Conclusion

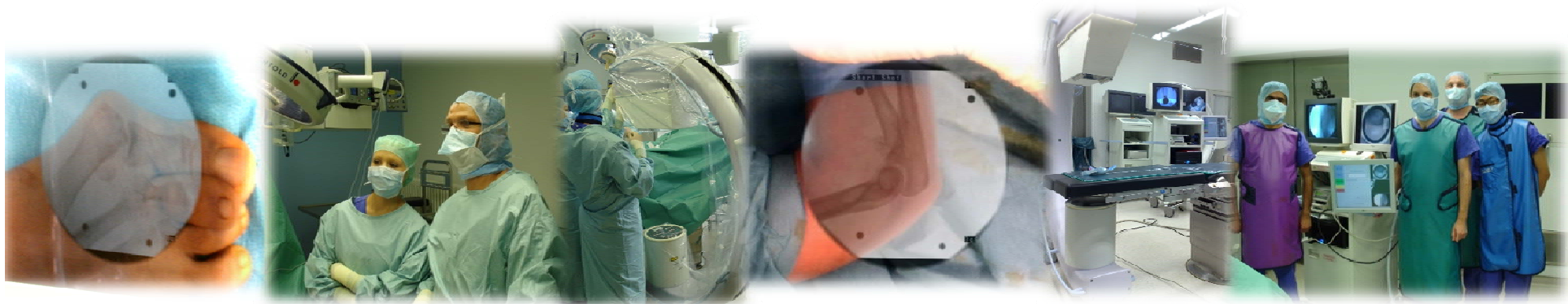
- 6DOF C-arm model was proposed and implemented,
    - paves the way for many computer assisted clinical applications
      - automatic C-arm positioning for parallax-free X-ray stitching
      - accurately positioning C-arm w.r.t. patient for smooth transform of the CT-based pre-operative planning into OR
  - The C-arm repositioning task was chosen to
    - evaluate our developed 6DOF C-arm system
    - show the improved accuracy of using the 6DOF model over the 5DOF model
  - C-arm systems with known relative pose information
    - external tracking or X-ray marker pattern
-



## Acknowledgement

- Thanks to Trauma Surgery Department, Klinikum Innenstadt, LMU Munich
- Our colleagues at NARVIS lab

# Thank you for your attention



- CAMC system has been developed with partial support from Siemens Healthcare



**END OF PRESENTATION**

---