

# Online Error Correction for the Tracking of Laparoscopic Ultrasound

Diploma Thesis

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20th July 2007



# Laparoscopic Ultrasound

- Laparoscopic ultrasound is widely used in abdominal surgery.
- Because of the missing visual feedback, determination of the flexible ultrasound transducer tip's pose is often difficult for the surgeons.  $\Rightarrow$  Navigation and augmented visualization can provide great benefits.
- Electromagnetic systems are the only currently available means to determine the transducer tip's pose inside the patient. Optical tracking is not usable, because no direct line of sight can be maintained.
- The electromagnetic field can be distorted by various static (OR table) or dynamic sources (surgical instruments).  $\Rightarrow$  Clear need for error detection and correction



# Related Work

- Existing techniques for error correction usually rely on a precalibrated distortion function, e.g. lookup tables or polynomial models are used.
- Drawback: only static errors can be compensated and the calibration procedure has to be repeated for every new OR setup.

We introduce two new approaches for error detection and correction for the tracking of laparoscopic ultrasound.



# Setup

We use ...

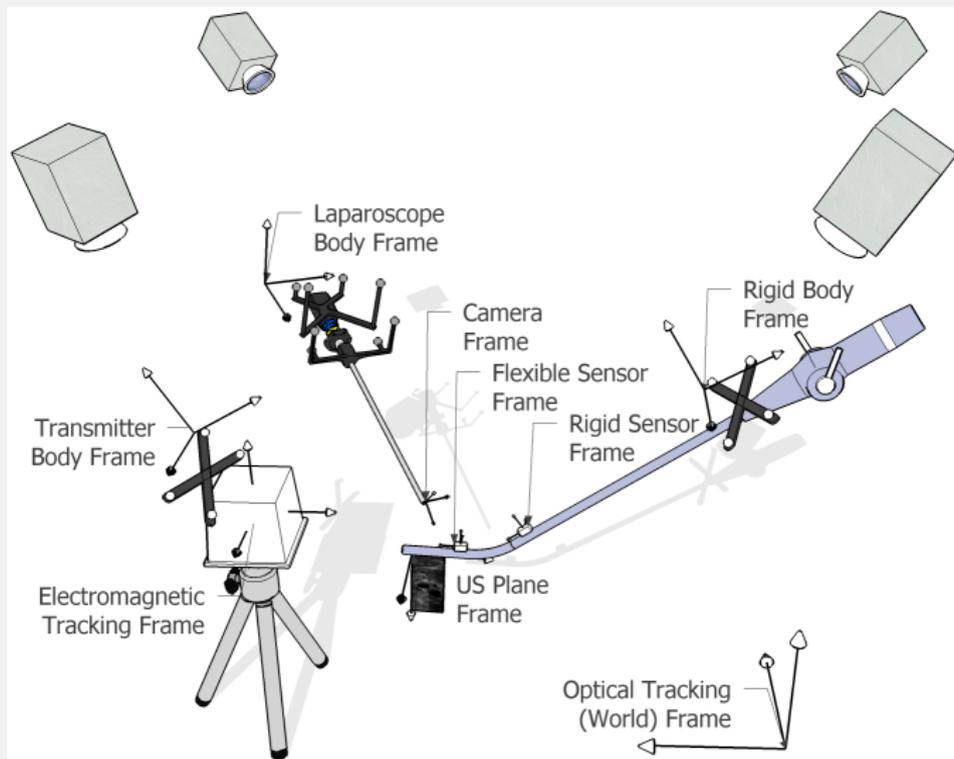
- laparoscopic ultrasound transducer
- “3D Guidance” electromagnetic tracker
- “ARTtrack2” tracking cameras & “DTrack” software
- laparoscope (with oblique 30° optic)
- visualization workstation with CAMPAR

We attach ...

- two EMT sensors to the transducer shaft and tip
- two OT bodies to the transducer shaft and tip
- one OT body to the EMT transmitter
- two OT bodies to the laparoscope



# Setup



# Calibration

We have to calibrate . . .

- laparoscope camera geometry (relative to OT body)
- transformation from the EMT coordinate frame to the transmitter OT body
- transformation from the shaft/tip EMT sensor to the shaft/tip OT body
- transducer tip resp. shaft axes (relative to EMT sensors)
- (temporal offset between the different tracking systems)

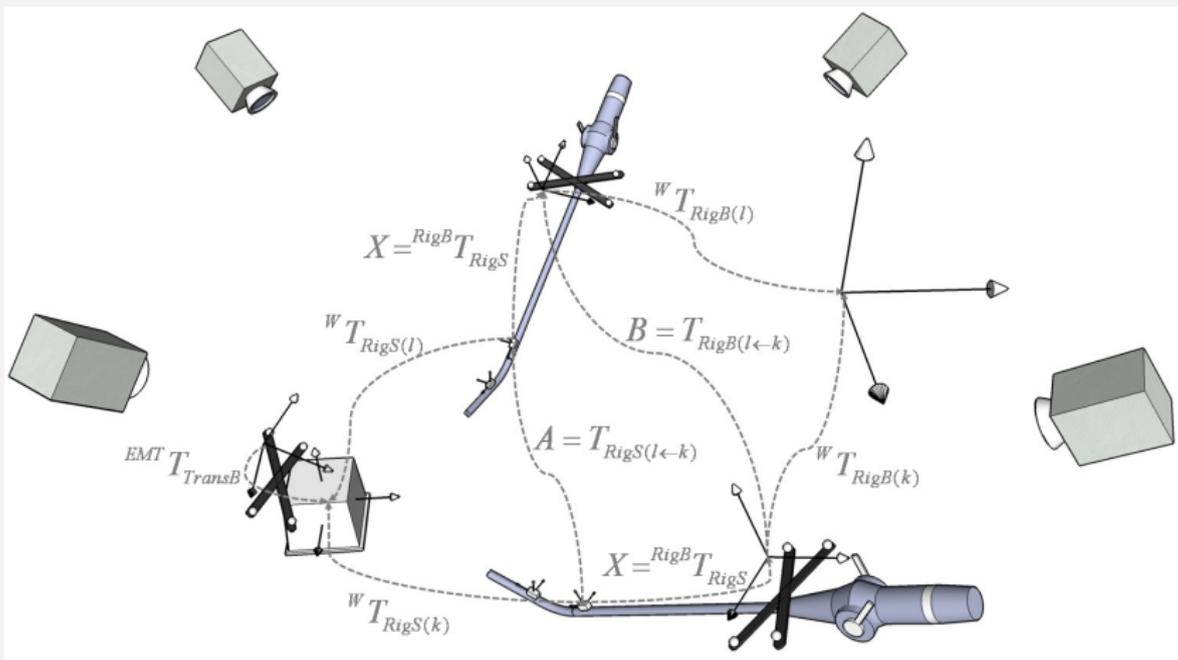
Laparoscope camera calibration is done using standard techniques (OpenCV with checkerboard calibration pattern). Special attention has to be paid to the calibration of the oblique viewing axis<sup>1</sup>.

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<sup>1</sup>Yamaguchi *et al.*: “Development of a camera model and calibration procedure for oblique-viewing endoscopes”, CAS 2004.



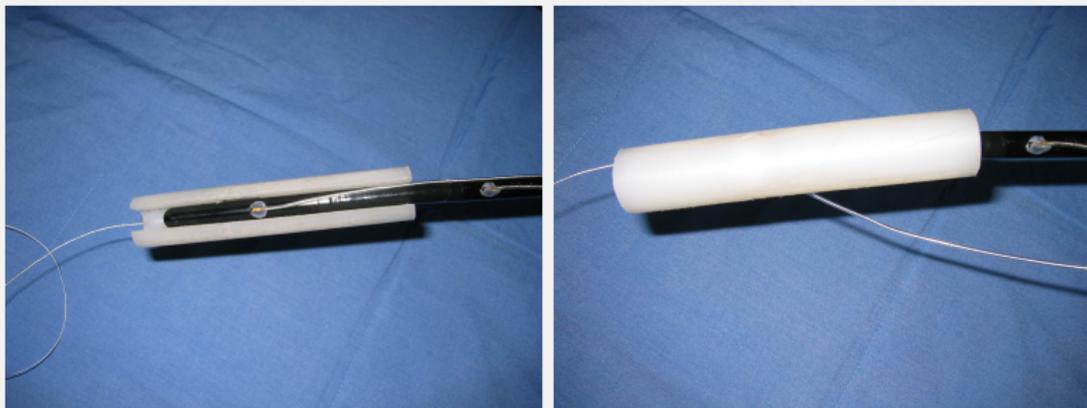
# Hand-Eye Calibration: "BX = XA"



$$T_{\text{Rig}^B(l \leftarrow k)} \cdot \text{Rig}^B T_{\text{Rig}^S} = \text{Rig}^B T_{\text{Rig}^S} \cdot T_{\text{Rig}^S(l \leftarrow k)}$$



# Axis Calibration



We manufactured a plastic calibration phantom, which fits the transducer and has a hole at one end for an additional “axis calibration sensor”.



# Axis Calibration

Calibration of the tip axis is done as follows:

- 1 The calibration phantom is slid over the transducer tip and rotated around the transducer.
- 2 The position of the calibration sensor relative to the tip sensor is computed and stored in regular intervals.  $\Rightarrow$  Ring-shaped point cloud of measurements
- 3 The phantom is reversed, slid over the tip, and rotated around the transducer again.  $\Rightarrow$  Second ring-shaped point cloud
- 4 All measurements have the same distance to the tip axis, so a cylinder surface is numerically fitted to them.  $\Rightarrow$  The axis of the resulting cylinder is our transducer tip axis.

This is repeated for the shaft axis.



# Transducer Bending

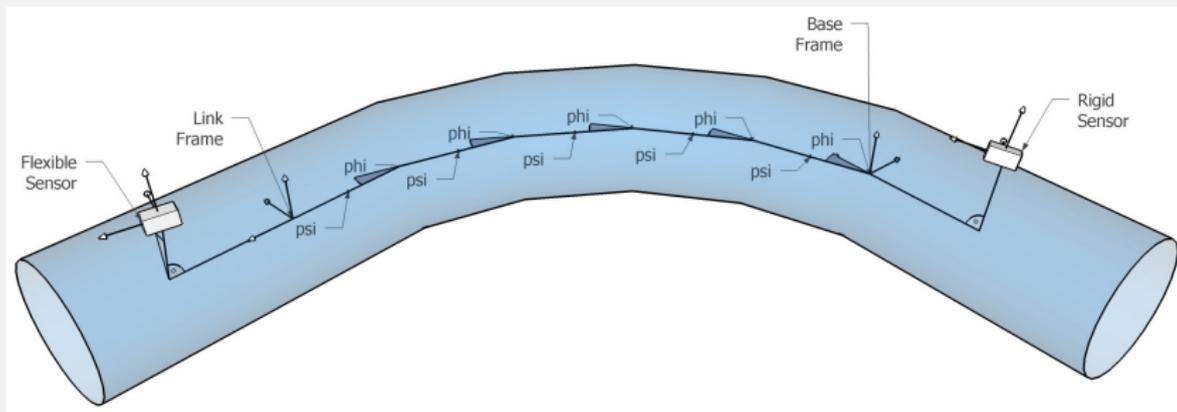


- Observation: no single joint, but lengthy bending region
- Single links allow either horizontal or vertical movement.
- 6DOF for EMT measurements, but only 2DOF for transducer tip motion  $\Rightarrow$  redundancy



# Model of Tip (Sensor) Movement

Chain of (parameterized) transformations from shaft sensor to tip sensor:



$$Tip^S \mathbf{T}_{Link} \text{ (6DOF)} \quad Link \mathbf{T}_{Base} \text{ (4DOF)} \quad Base \mathbf{T}_{ShaftS} \text{ (5DOF)}$$



# Model of Tip (Sensor) Movement

$^{Base}T_{ShaftS}$  (5DOF):

- 2DOF: rotation, align sensor with axis
- 2DOF: translation to axis
- 1DOF: translation along axis
- Rotation about transducer axis not fixed

$^{Link}T_{Base}$  (4DOF):

- 1DOF: number of links
- 2DOF: rotation ( $\phi$  horizontal and  $\psi$  vertical)
- 1DOF: translation along axis

$^{TipS}T_{Link}$  (6DOF):

- 3DOF: translation (along axis & from axis to sensor)
- 3DOF: rotation (about axis & align with sensor)



# Model Parameters

- All parameters (except  $\phi$  and  $\psi$ ) remain constant for a given configuration and can be computed offline.
- $\phi$  and  $\psi$  remain to be computed online, because they depend on the levers' positions and external forces.

Computation becomes easy, once the transducer axes are known.  
Then only the following parameters remain:

- Translation along shaft axis
- Number of links (fixed)
- Length of bending region (fixed)
- Rotation about transducer axis
- Translation along tip axis



# Modeling the Tip Sensor

- At run-time the angles  $\phi$  and  $\psi$  are optimized numerically.
- We minimize the position difference from the model to the tip sensor measurements, the orientation difference between them, or a combination of both.
- The model is anchored at the shaft OT body (via calibrated transformation) instead of the shaft EMT sensor, because the shaft sensor might be affected by distortions as well.



# Shaft Sensor Based Error Correction

The transducer shaft is tracked by both EMT and OT, so we can compute the difference between ...

- 1 the position of the shaft sensor, as measured by EMT and transformed into the OT coordinate frame, and
- 2 the calibrated position of the shaft sensor relative to the shaft OT body (whose position is known from OT), transformed into the OT coordinate frame.

This difference is then “subtracted” from the tip sensor measurements, to compensate for the distortion of the electromagnetic field.

(Assumption: both sensors are affected similarly.)



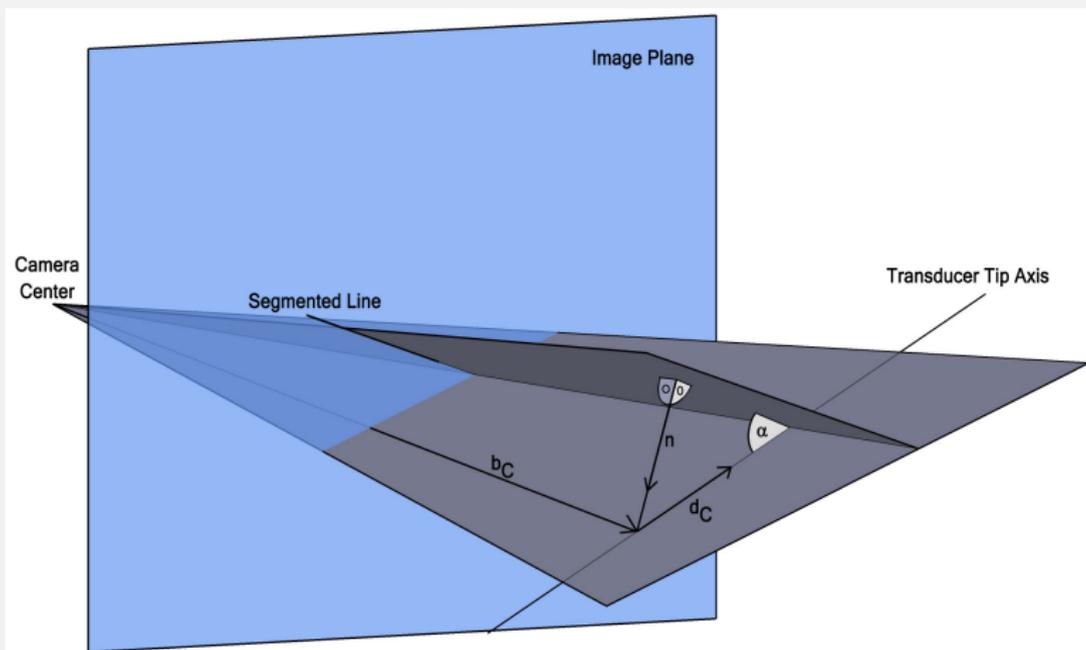
# Segmentation Based Error Correction

We utilize additional information available from the video images from the tracked laparoscope:

- 1 Extract edges from image using an edge filter and Hough transform.
- 2 Back-project extracted lines into space (using known camera geometry).
- 3 Compare to tracking information about the transducer tip and select lines belonging to the transducer tip.
- 4 Compute a correction transformation.



# Segmentation Based Error Correction



Back-projection of segmented line and comparison to tip axis



# Segmentation Based Error Correction

- Compute distance of tip axis “base point” to back-projected plane and angle between tip axis and plane.
- Select lines probably belonging to the transducer.
- Check for correct diameter (distance between minimum and maximum distance).
- Select lines probably belonging to the transducer edges.
- Compute correction transformation (translation & rotation).



# Error Correction Methods

Three different error correction methods:

- 1 (Simple) Shaft sensor based error correction
- 2 Model based error correction
- 3 Segmentation based error correction

Model and segmentation based error correction can be combined (see later).



# Error Detection

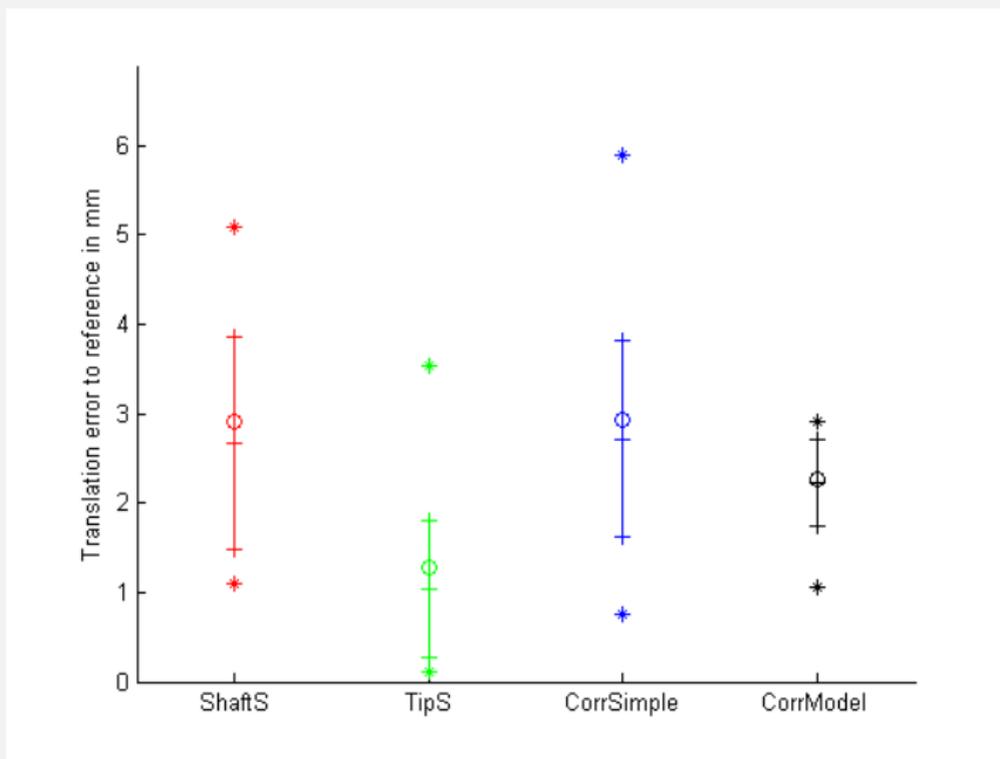
We can always compute two certain distances:

- 1 Position difference between calibrated (HEC & OT) and measured (EMT & HEC & OT) position of shaft sensor
- 2 Position difference between uncorrected tip sensor and modeled tip sensor

Both distances can be used to predict tracking errors of the tip sensor. If the distance exceeds a certain threshold, the tip sensor measurements are assumed to be distorted.



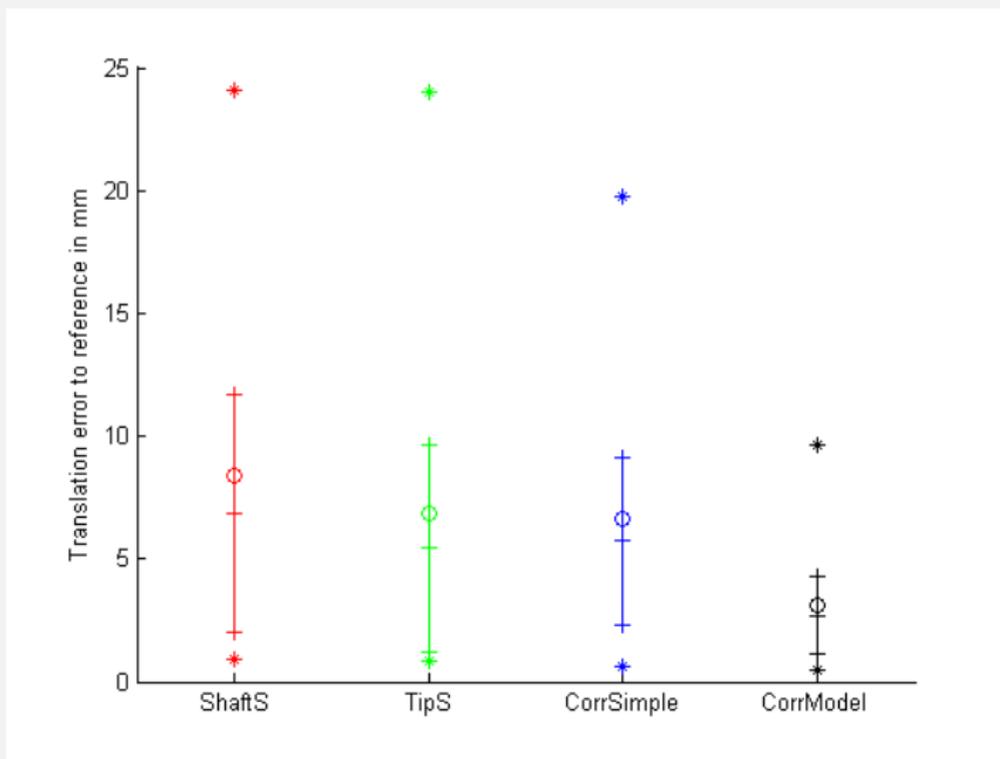
# Error Correction: Undistorted Field



RMS: 2.91 / 1.28 / 2.92 / 2.27 mm



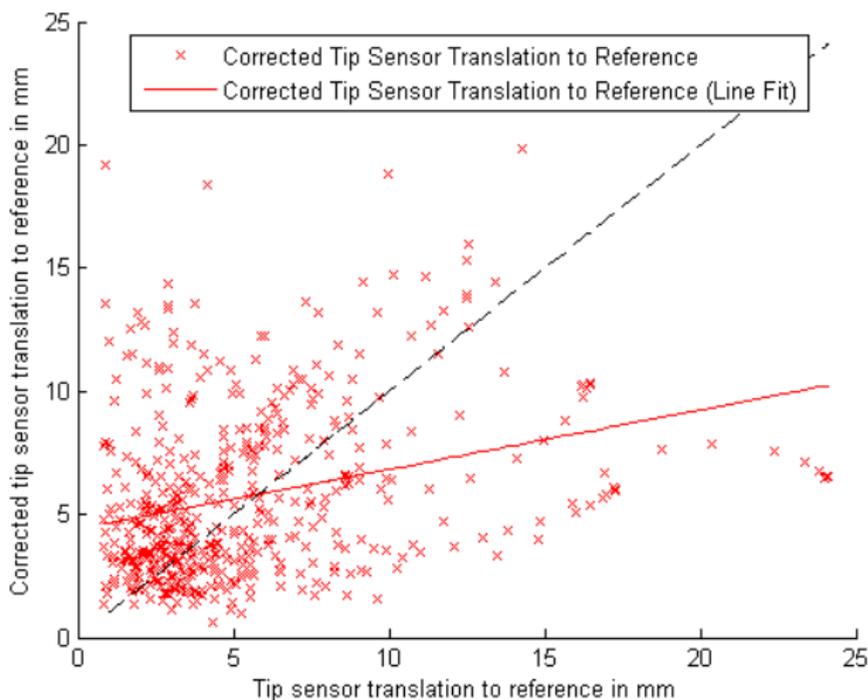
# Error Correction: Distorted Field



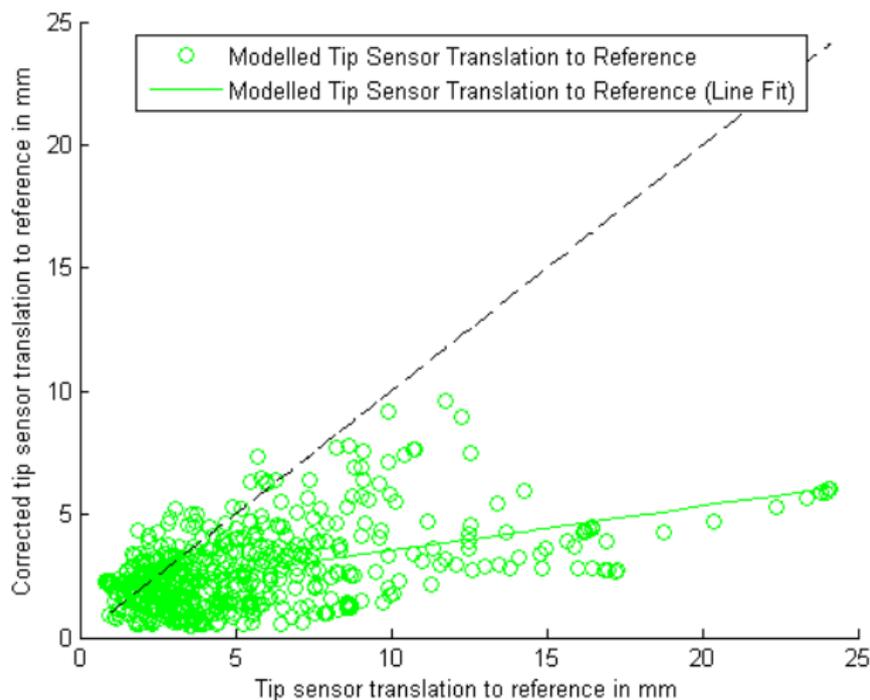
RMS: 8.39 / 6.91 / 6.67 / 3.15 mm



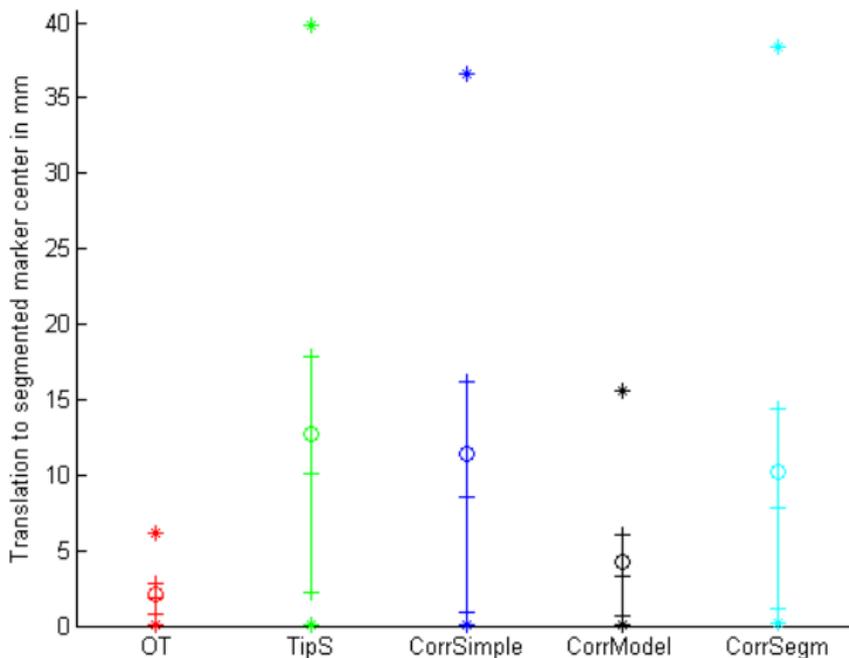
# Error Correction: Shaft Sensor Based



# Error Correction: Model Based



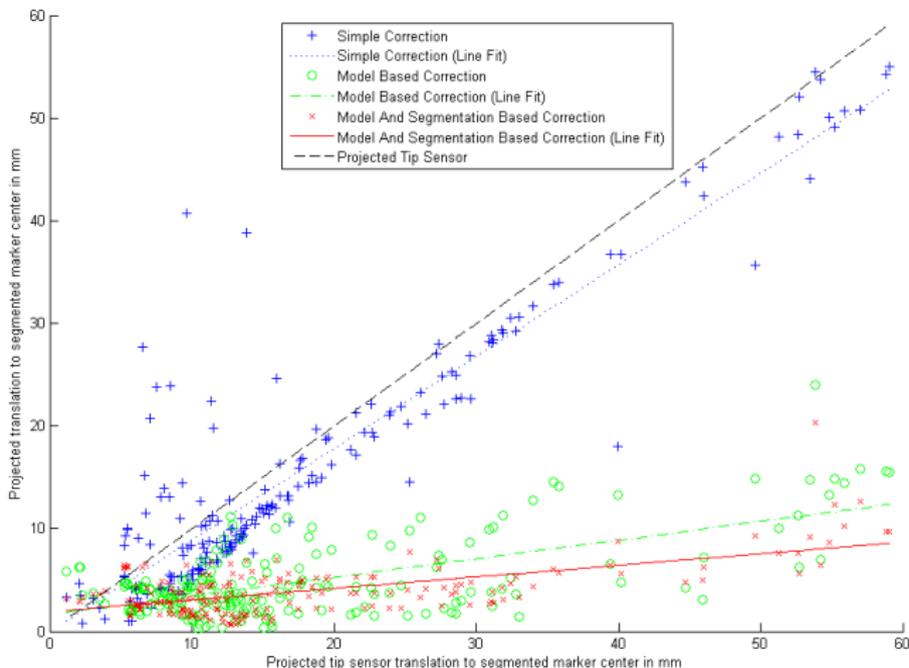
# Error Correction: Overlay Accuracy



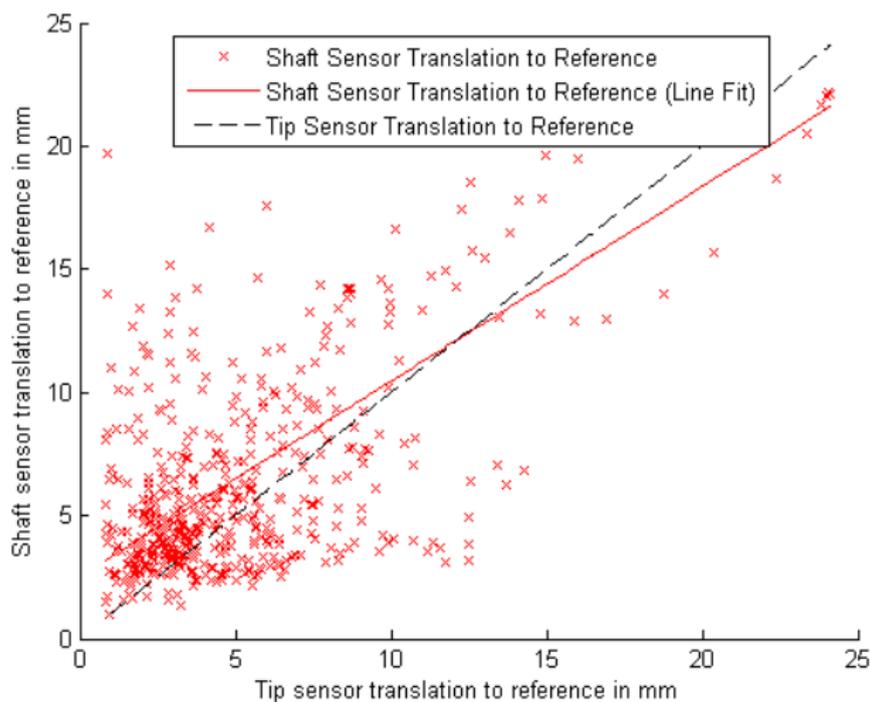
RMS: 2.08 / 12.71 / 11.45 / 4.26 / 10.19 mm



# Error Correction: Overlay Accuracy



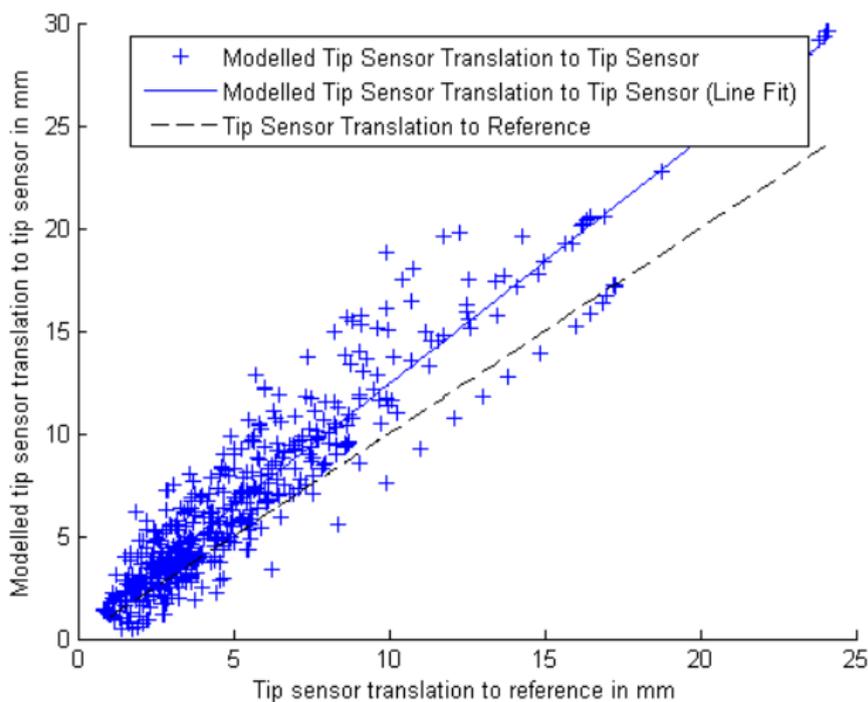
# Error Detection: Shaft Sensor Translation



Correlation coefficient: 0.69



# Error Detection: Model-Sensor Translation



Correlation coefficient: 0.95

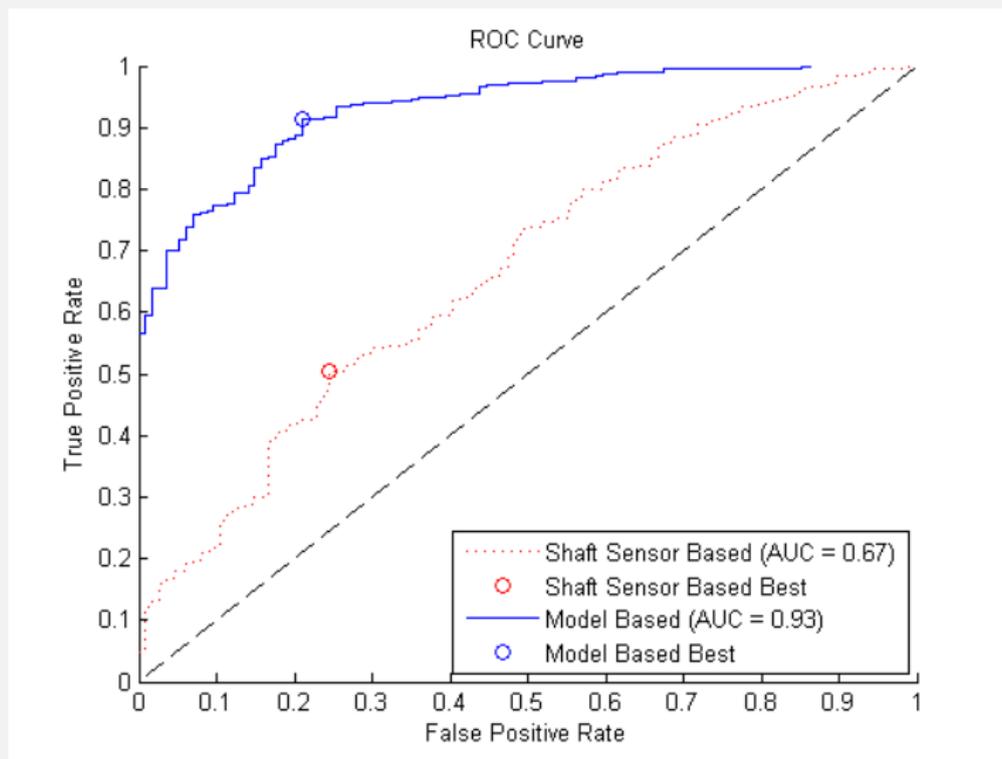


# Error Detection

- Trade-off between sensitivity (recognition of errors) and specificity (recognition of non-errors)
- A “Receiver Operating Characteristic” (ROC curve) illustrates the performance of all possible thresholds.
- Each point on the curve represents one possible threshold value and the trade-off between sensitivity and specificity, if it was used as the threshold.



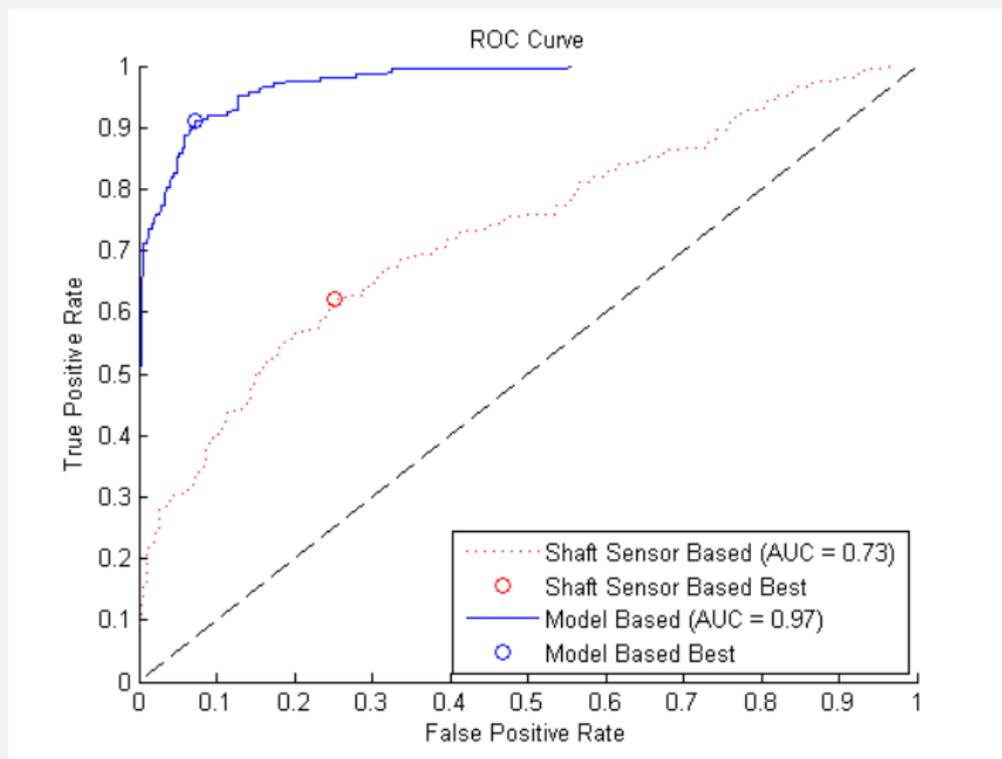
# ROC Curve: Predicting an Error $> 2.5$ mm



Model based: 91% / 79%, sensor based: 50% / 75%



# ROC Curve: Predicting an Error $> 5.0$ mm



Model based: 91% / 93%, sensor based: 62% / 75%



# Future Work

- Use one sensor only: after determining the transformation from tip sensor to tip OT body, the model can be built using OT instead of EMT, so the shaft sensor is not needed any more.
- Redundantly tracked transducer shaft: generation of a distortion function on-the-fly?
- More robust techniques for segmentation



# Conclusion

- Shaft sensor based error correction does not gain improvements.
- Shaft sensor based error detection performs similar to the state of art<sup>23</sup>.
- Model based error correction significantly reduces position error and is first proposed method to compensate dynamic errors with the tracking of flexible laparoscopic instruments.
- Model based error detection significantly improves the state of art.

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<sup>2</sup>Birkfellner *et al.*: “Concepts and results in the development of a hybrid tracking system for cas”, MICCAI 1998.

<sup>3</sup>Mucha *et al.*: “Plausibility check for error compensation in electromagnetic navigation in endoscopic sinus surgery”, CARS 2006.

