Multimodal Tracking of Three-dimensional Maxillo-dental Changes of Bones and Soft-tissues Over Time

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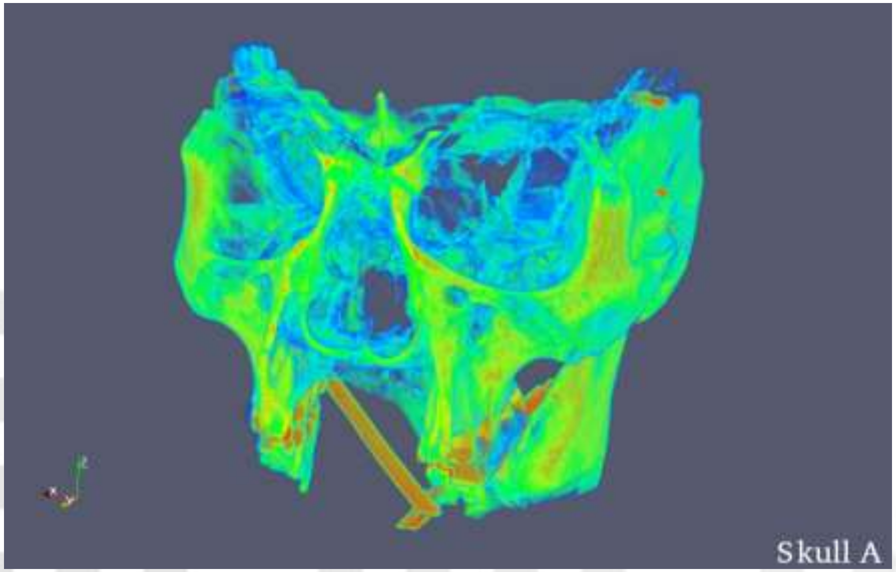
Main Issues

- How to segment volumetric data?
- How good is CBCT geometry?
- How to combine CBCT with Photogrammetry?
- How to do long-term registration?
- More modalities
- Conclusion

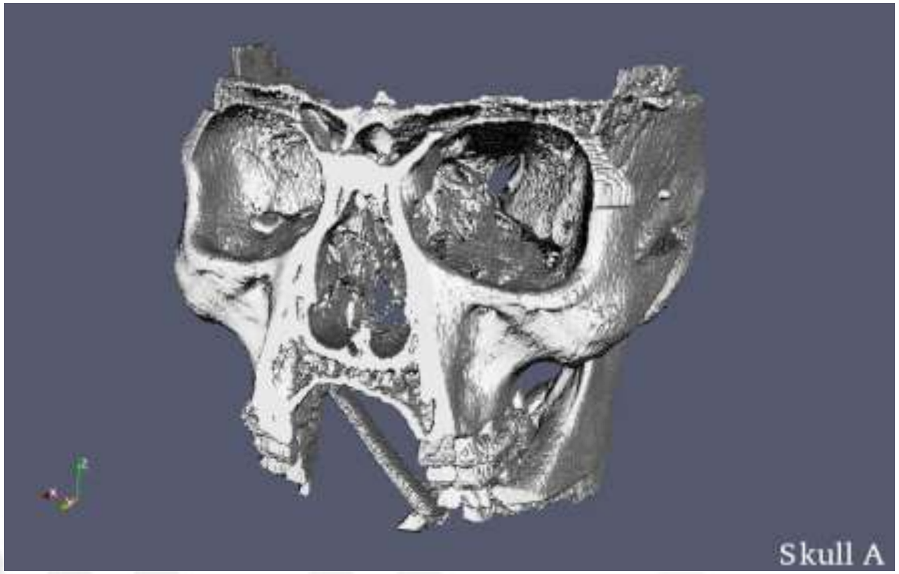
3D Difference After Six Months

Six Months Later

From Density to Geometry



Volumetric Density Data



Geometry Using Region Growing

Segmentation(1)

Problem: Structures easily detected by the human eye are difficult to specify for a computer

- Many different segmentation approaches and variations available

- Specific image acquisition protocols can ease segmentation difficulties, i.e. contrast agent

Segmentation(2)

- Automatic segmentation frequently segments too much, or not all structures

- Manual segmentation is usually too expensive for daily practice

- Semi-automatic segmentation with little interaction only: can consist of several steps

Segmentation(3)

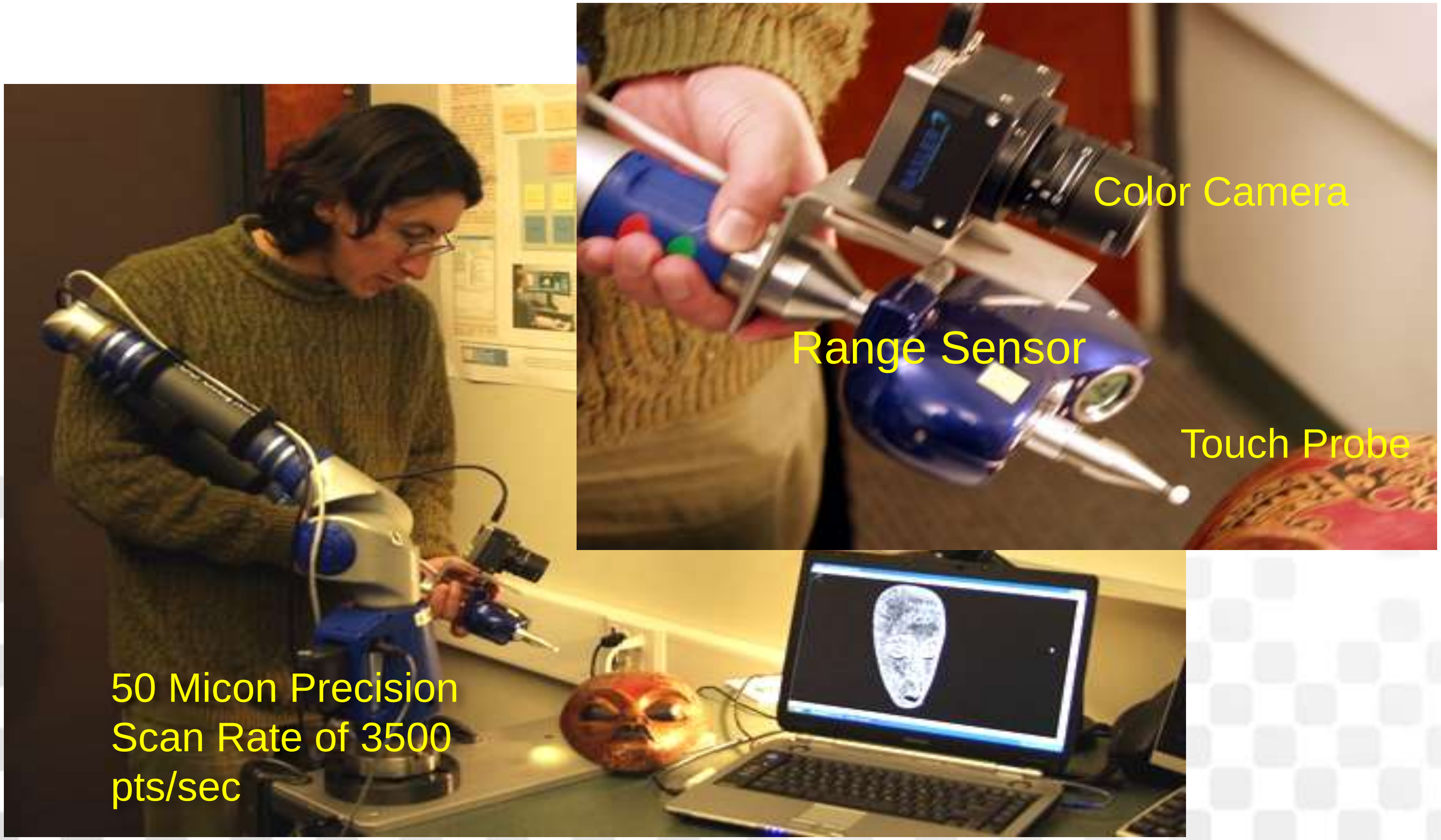
- Typical medical semiautomatic segmentation algorithm is **3D Region growing**
- Specify **seed point** inside structure of interest
- Specify **threshold interval** which describes material interfaces
- Successively selects neighbouring voxels until threshold interval is violated

Segmentation(4)

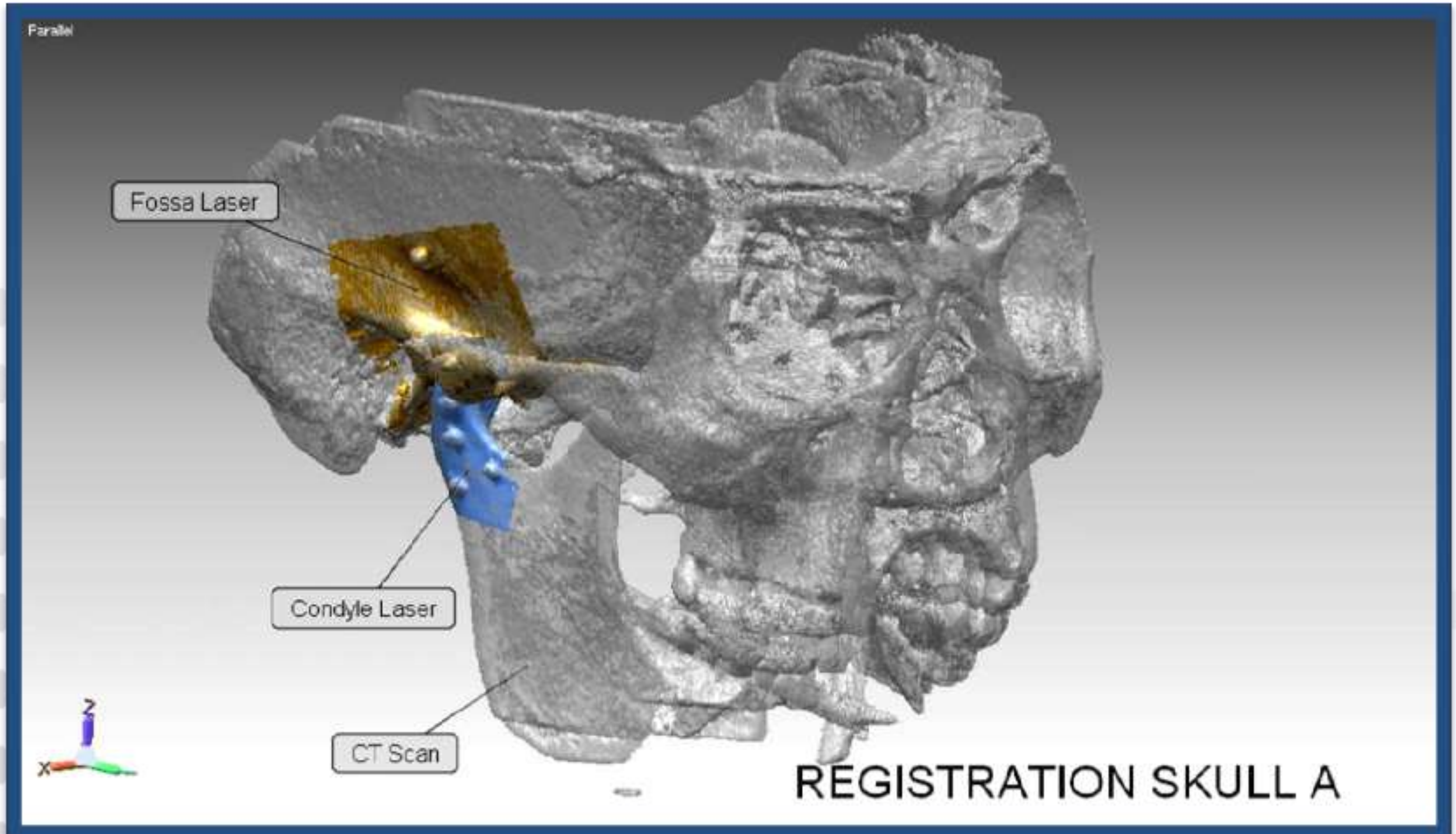
Potential problems of 3D region growing:

- Inappropriate threshold interval
- False/missing connections due to partial volume effect or signal attenuation
- Resolution too low
- Contrast too low; good contrast: feature intensity high, surrounding intensity low

AMMI Lab. Laser Scanner



Cone Beam CT vs Laser Scanner



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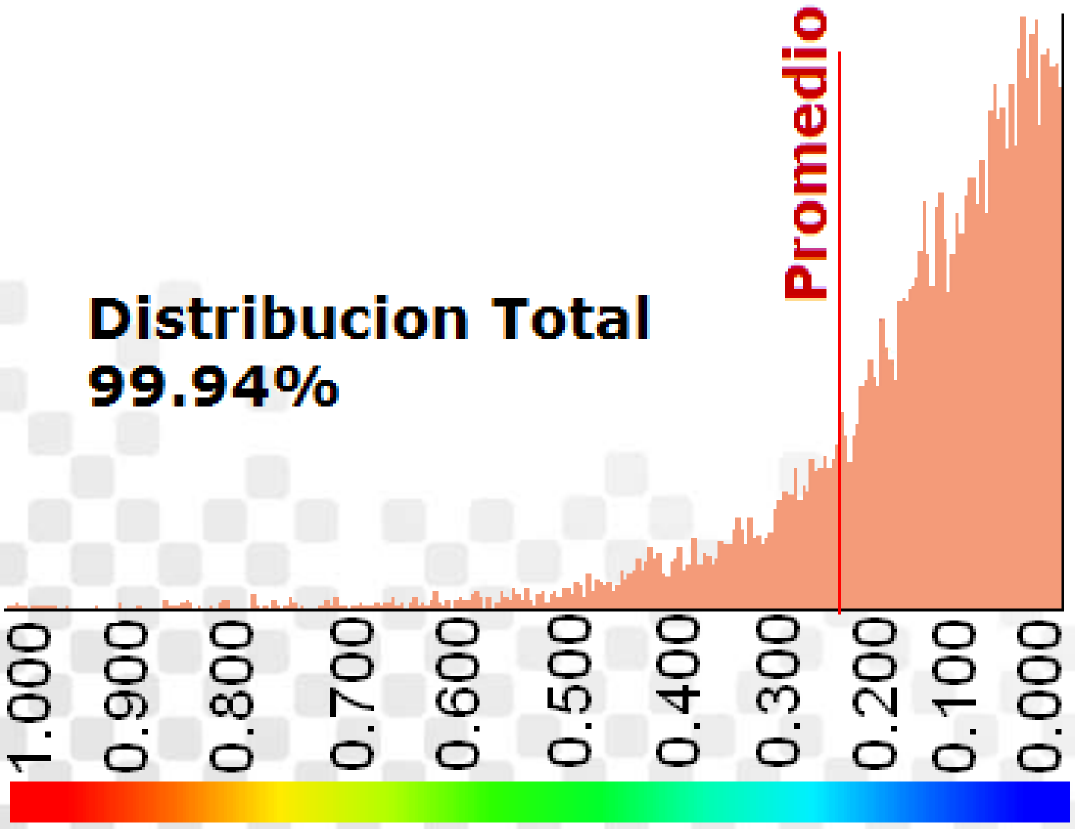
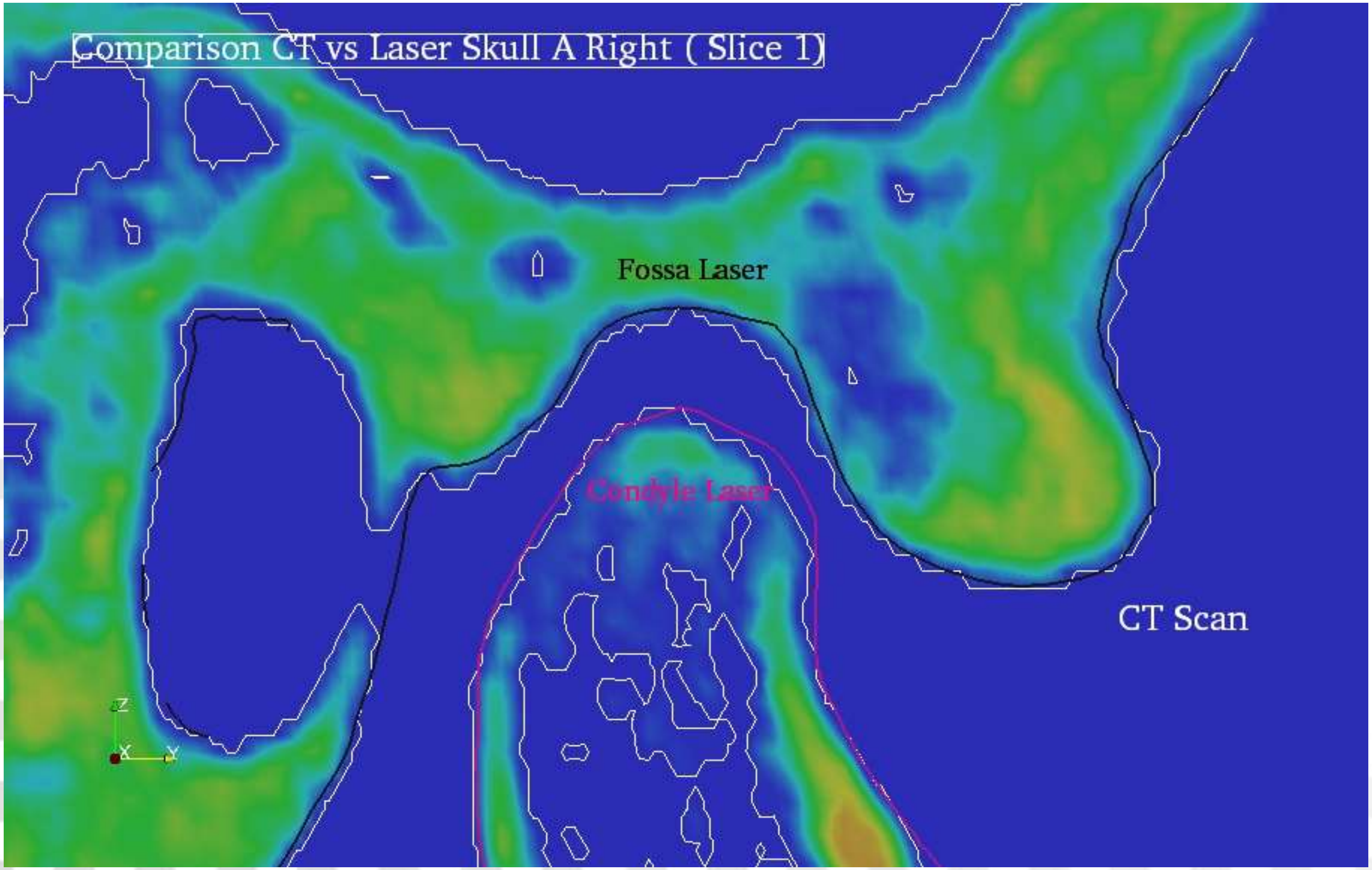
Final Precision

- An average difference of 0.12 mm with a two sigma variance of 0.4 mm was observed. There were no systematic biases observed.
- In a similar geometric accuracy study with a different CBCT unit, Marmulla et al. found an average image deviation of 0.13 mm which was below than the voxel size of 0.18 mm.
- Although a difference between CBCT and LS measurements were identified; CBCT appears to be sufficiently accurate to be used as a clinical tool.

Laser Scan vs CBCT

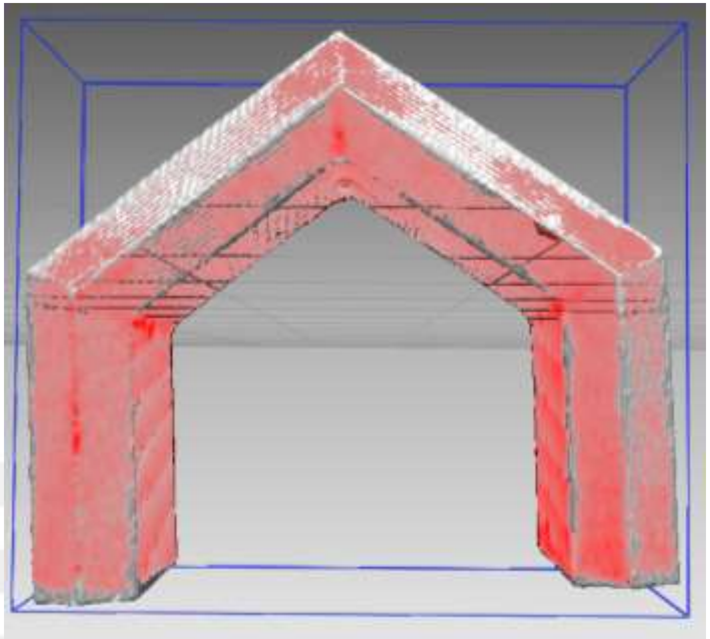


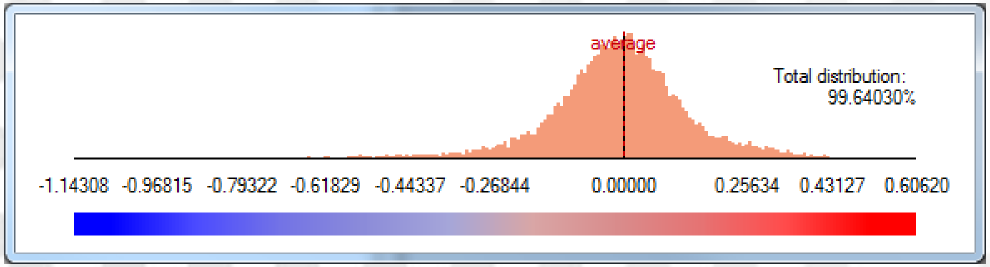
Problem with CT Segmentation



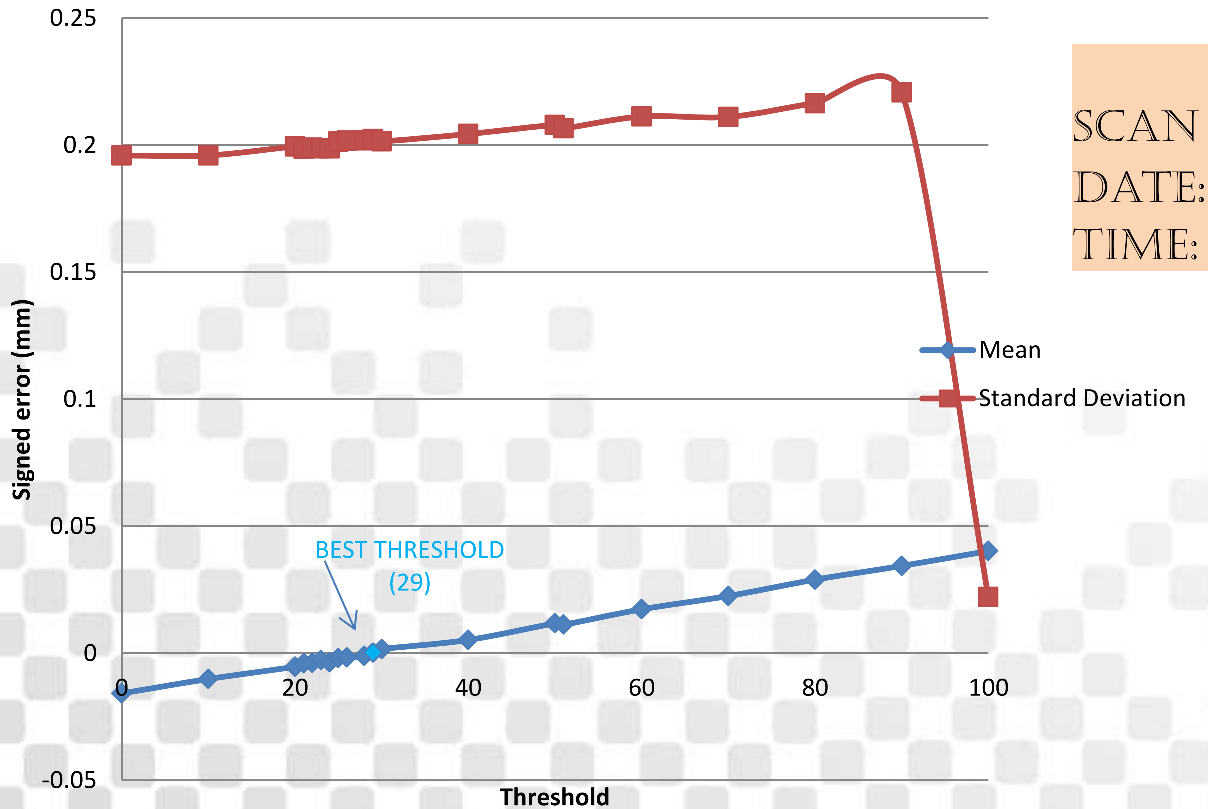
Determining an *Optimal* Threshold

- CBCT scans were taken on four different days at three different times
  - **COLD** – when the machine was first turned on
  - **1 hour** – after an hour of the machine being in use
  - **4 hours** – after four hours of the machine being in use
- For each time the CBCT was used and an optimum threshold was determined
- According to the data collected, the threshold is dependent on both time and date



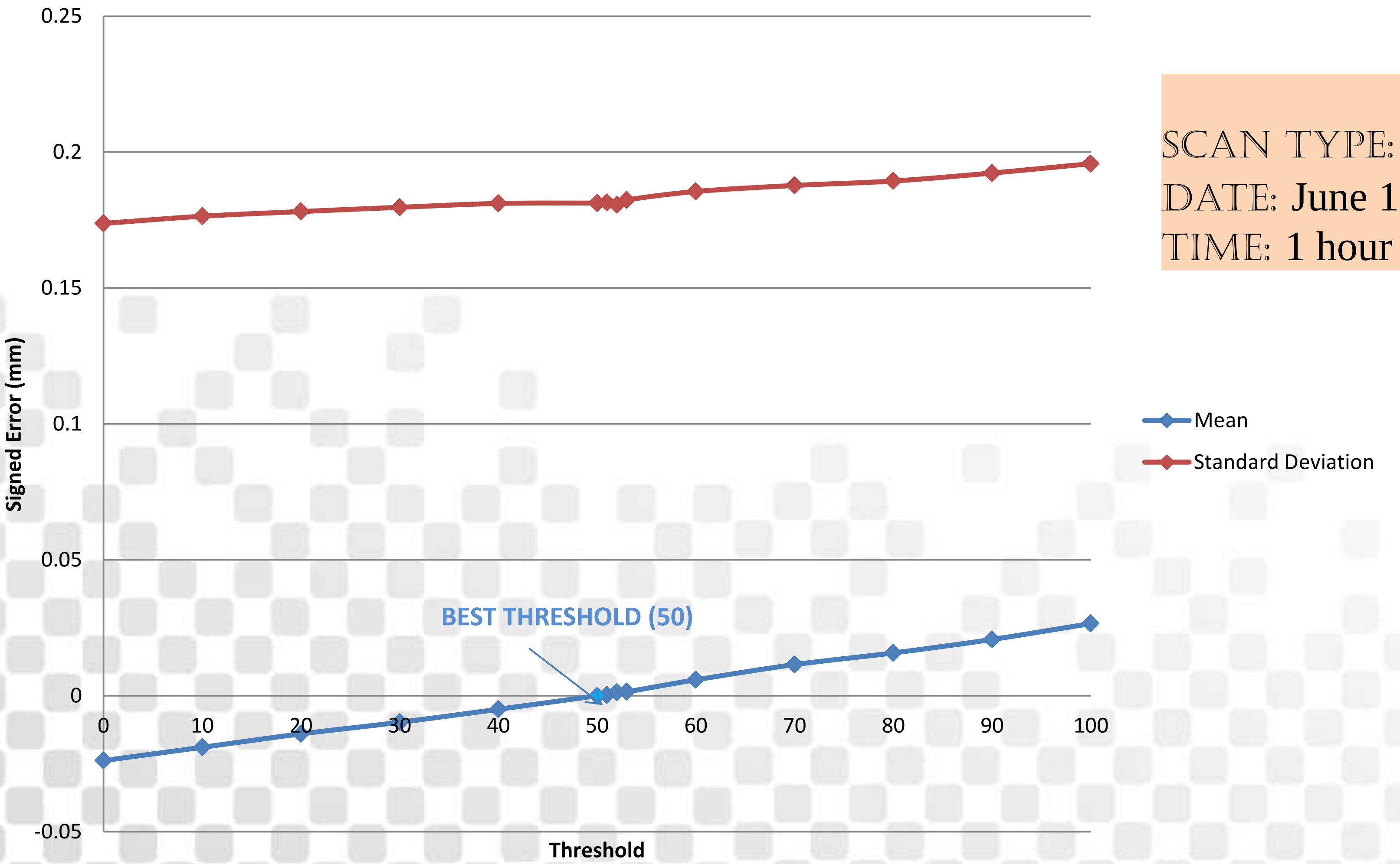


Signed Error of Different Thresholds on CBCT June1 (COLD)



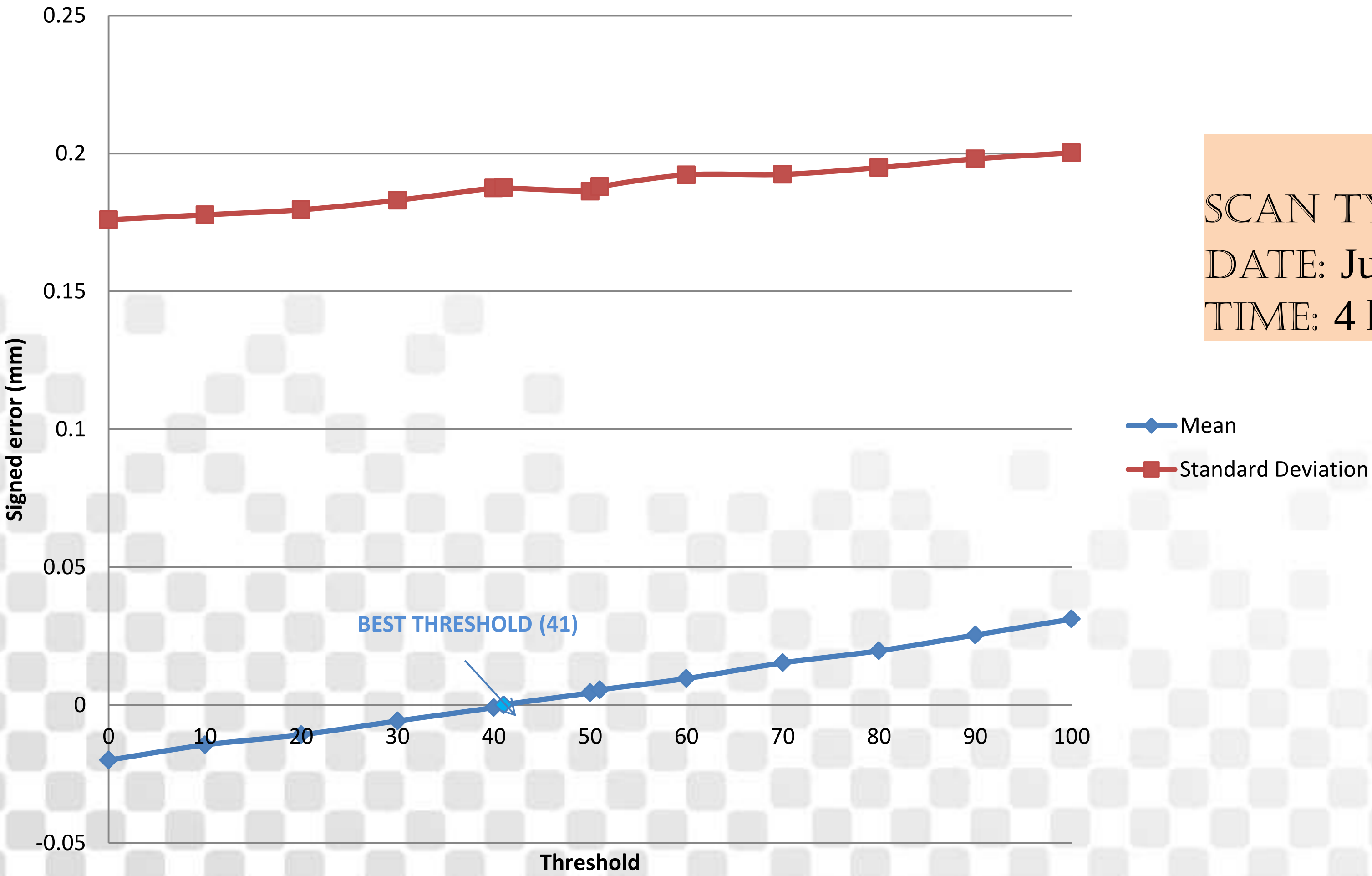
SCAN TYPE: CBCT
DATE: June 1
TIME: COLD

Signed Error of Different Thresholds on CBCT June1 (1hr)



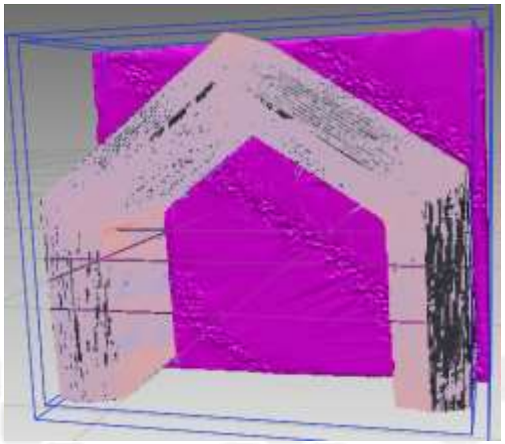
SCAN TYPE: CBCT
DATE: June 1
TIME: 1 hour

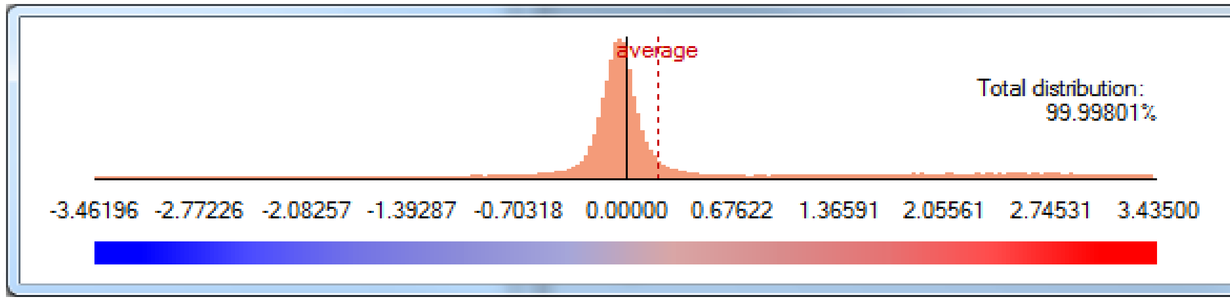
Signed Error of Different Thresholds on CBCT June1 (4hrs)



SCAN TYPE: CBCT
DATE: June 1
TIME: 4 hours

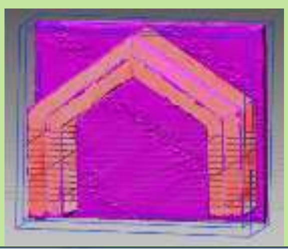
How Different Are CT & CBCT (COLD)?

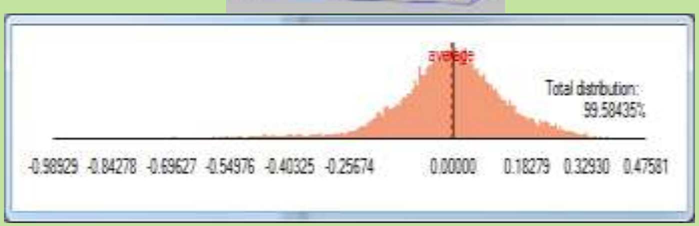




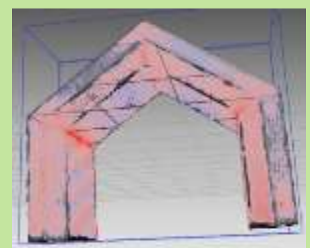
COMPARING TO THE REFERENCE MODEL

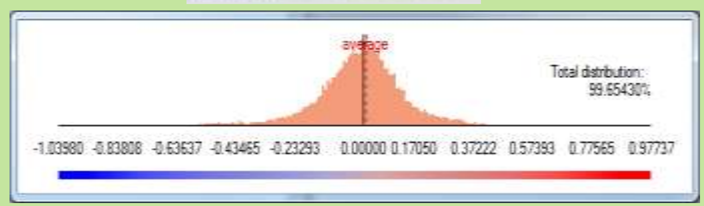
CT



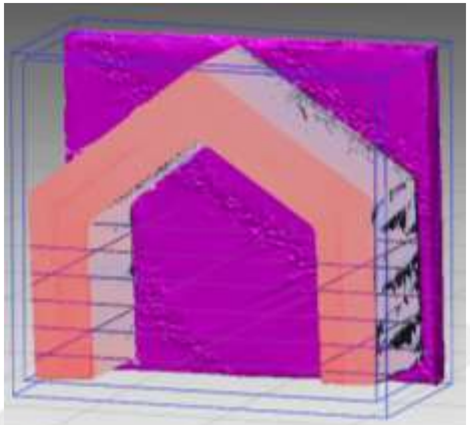


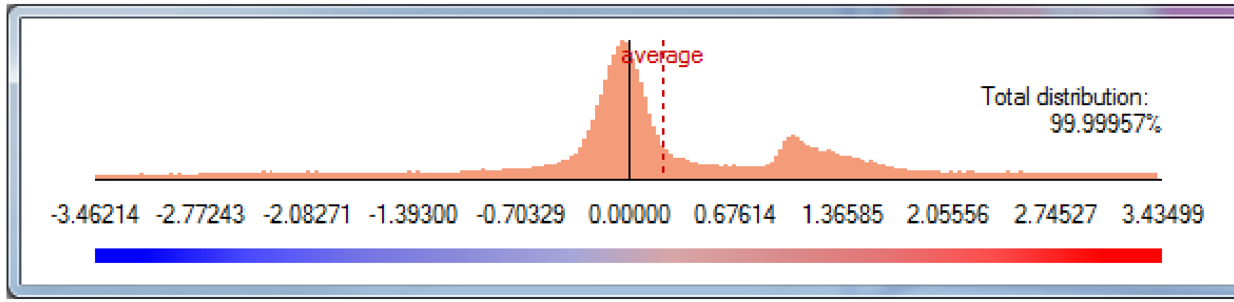
CBCT (COLD)





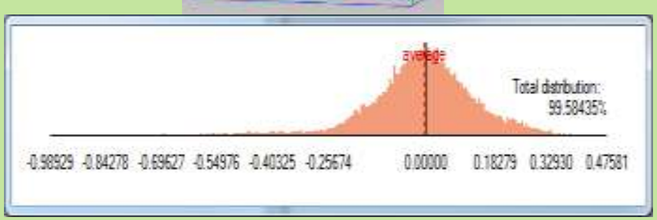
How Different Are CT & CBCT (1 hour)?



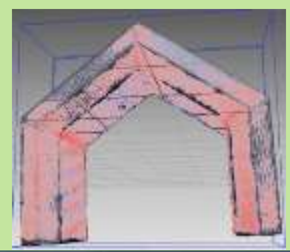


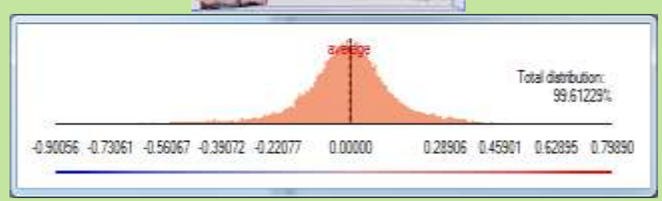
COMPARING TO THE REFERENCE MODEL

CT

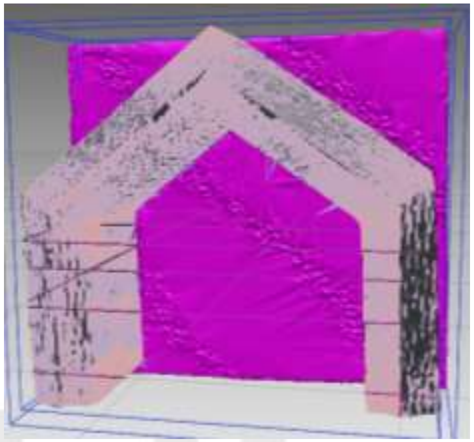


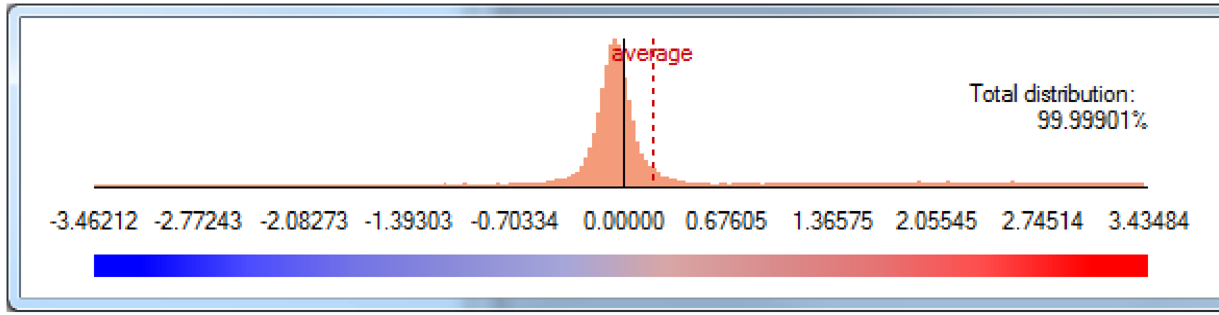
CBCT (1 hour)





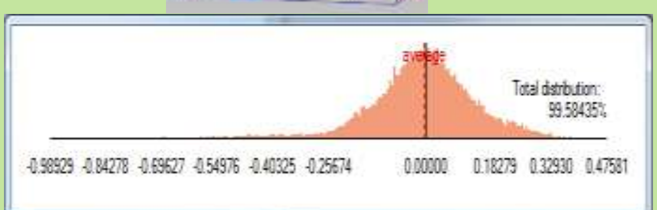
How Different Are CT & CBCT (4 hours)?



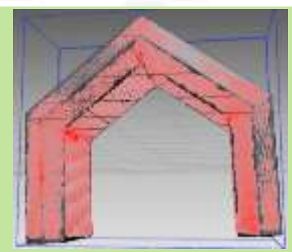


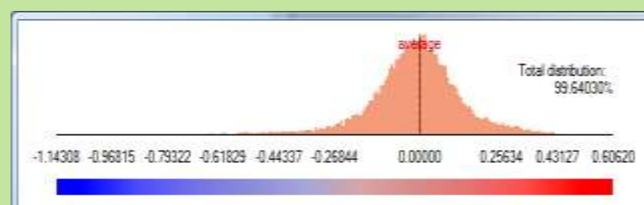
COMPARING TO THE REFERENCE MODEL

CT



CBCT (4 hours)



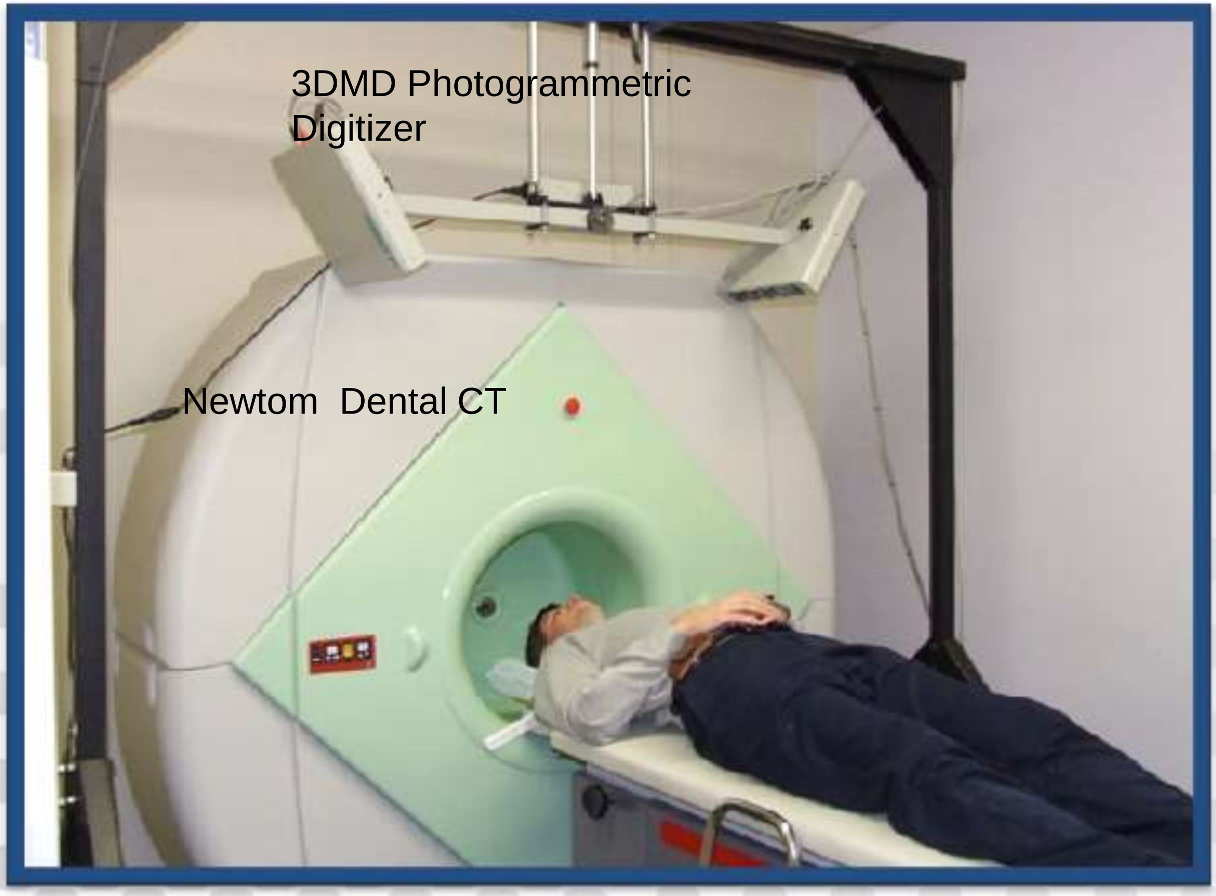


Factors Influencing Precision?

- Elliptical Interpolation for normal CT
- CT Reconstruction Algorithm
- Type of Sensors (CBCT vs Fan Beam CT)
- Sensor setting
- Filtering
- **Segmentation Algorithm**
- Signal Contrast
- CT Calibration

CBCT and Photogrammetry

3D Digitizing Facility Built at the UofA Faculty of Dentistry



Stereo Pairs of 3dMD

TOP

Left

Right

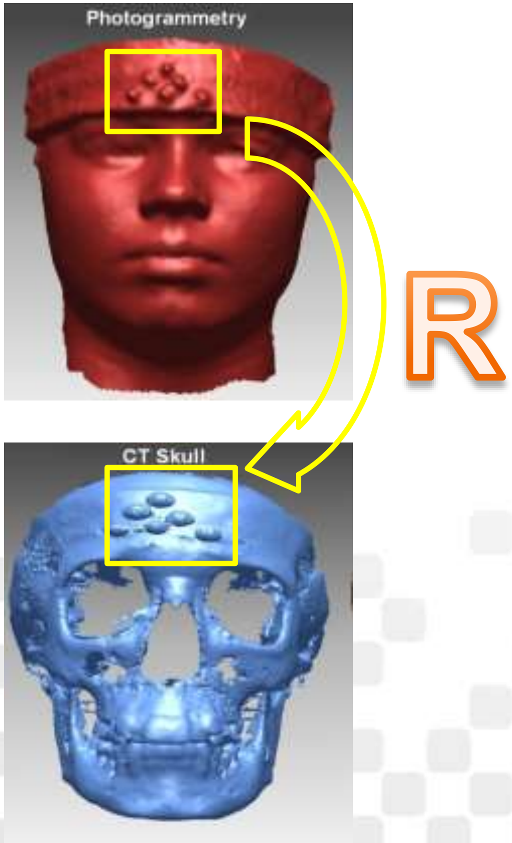
Texture

BOT

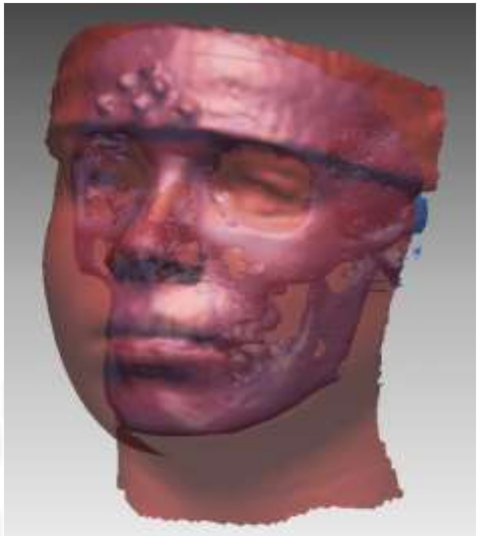
Textured
3D Model

Registration of Skin and CBCT Using Landmark

Patient With Tracking Targets Getting Scanned

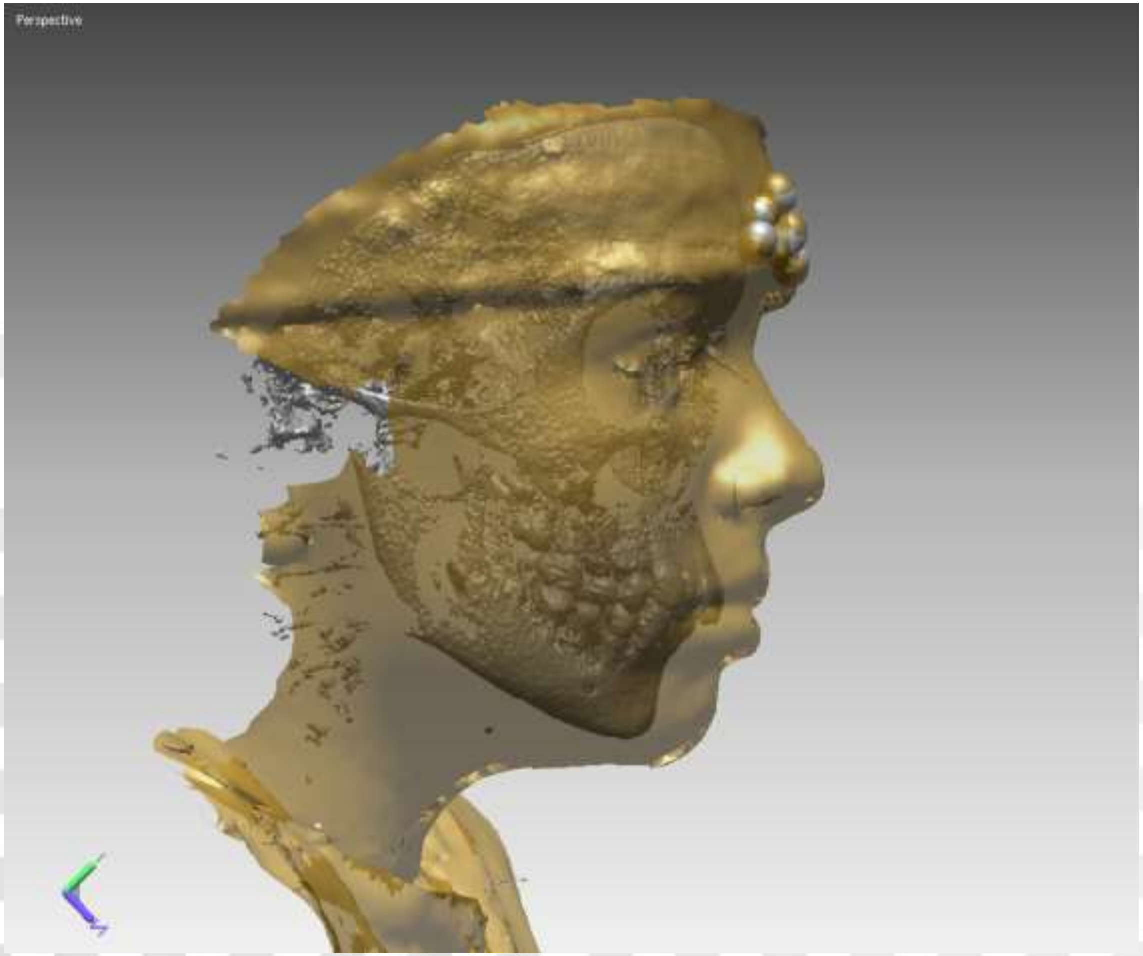


Bone geometry from CT Scan and Skin geometry from Photogrammetry

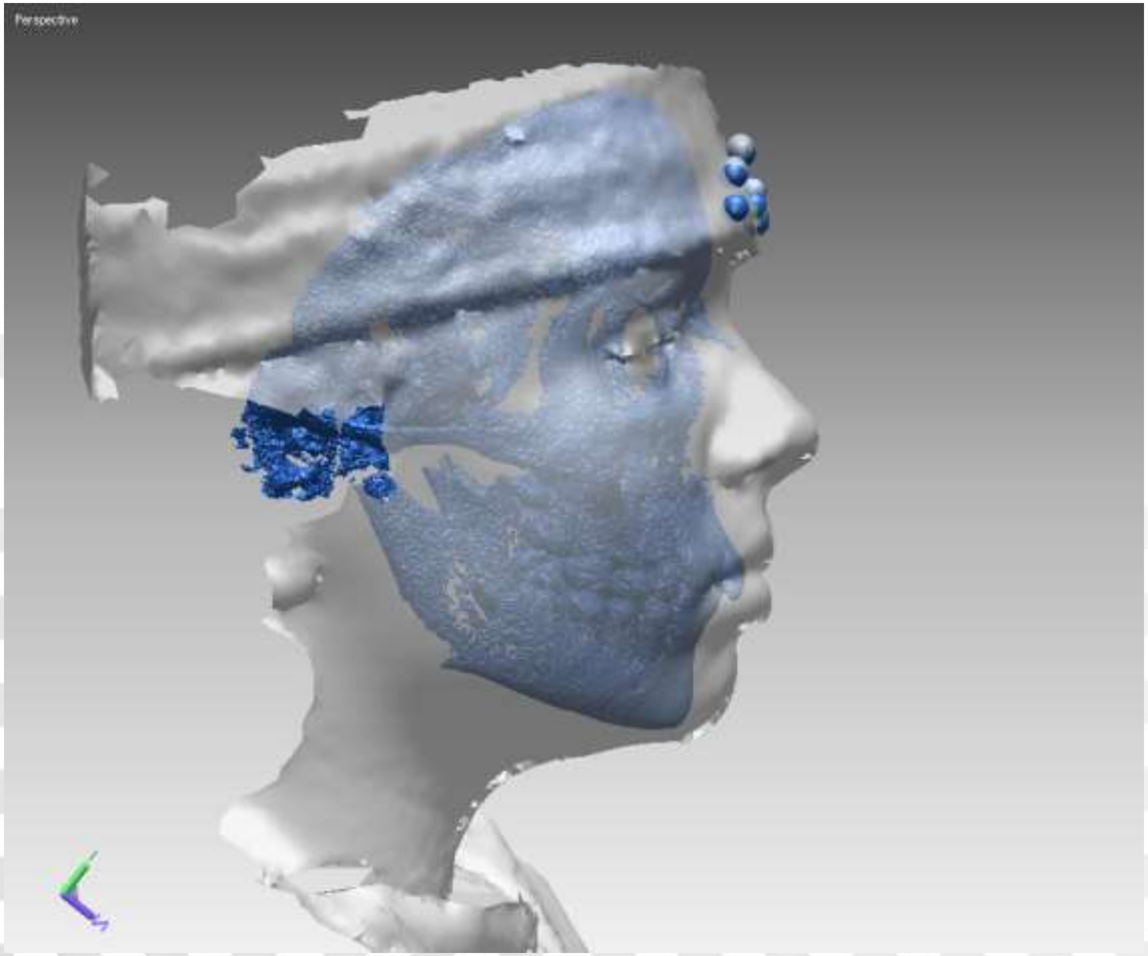


Registered Bone and Skin Geometries

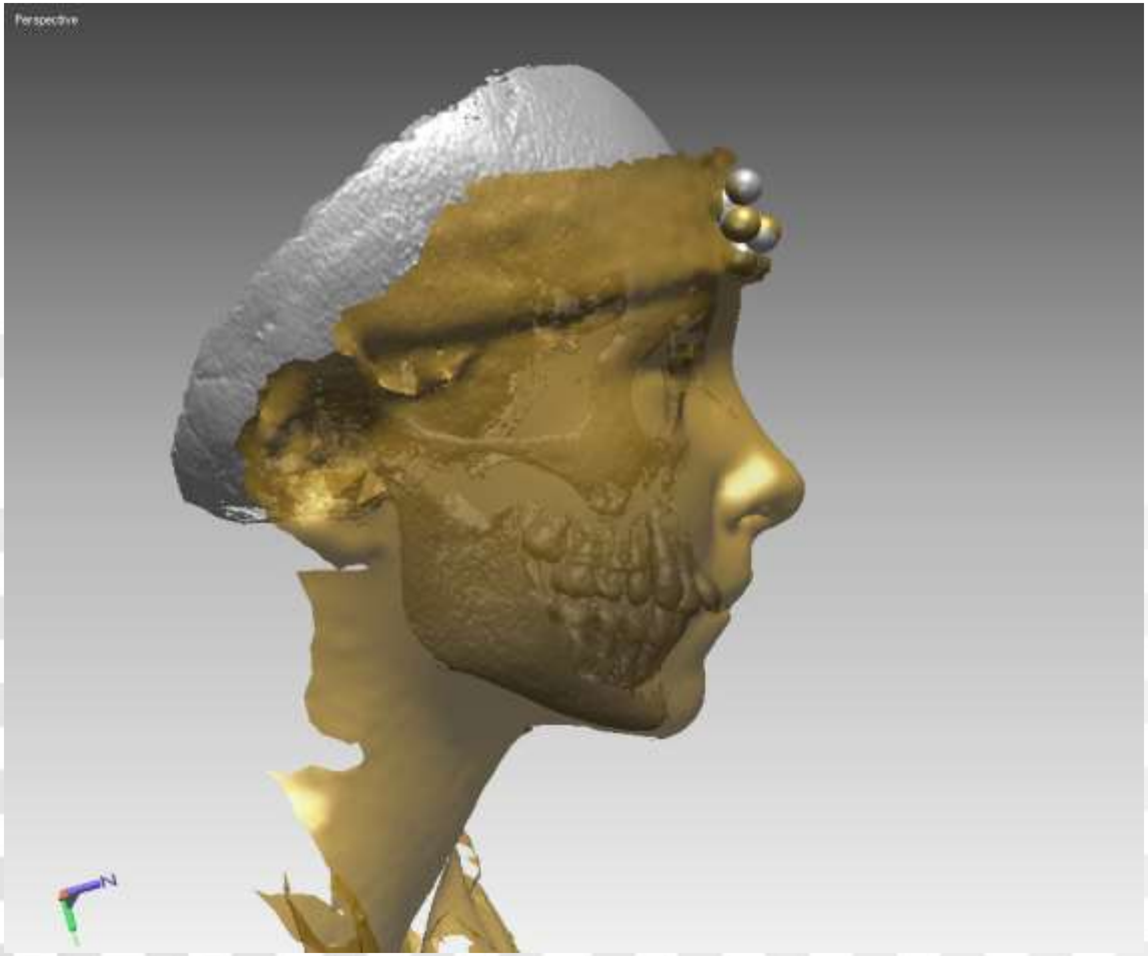
Patient 1 – Time 0 Registration



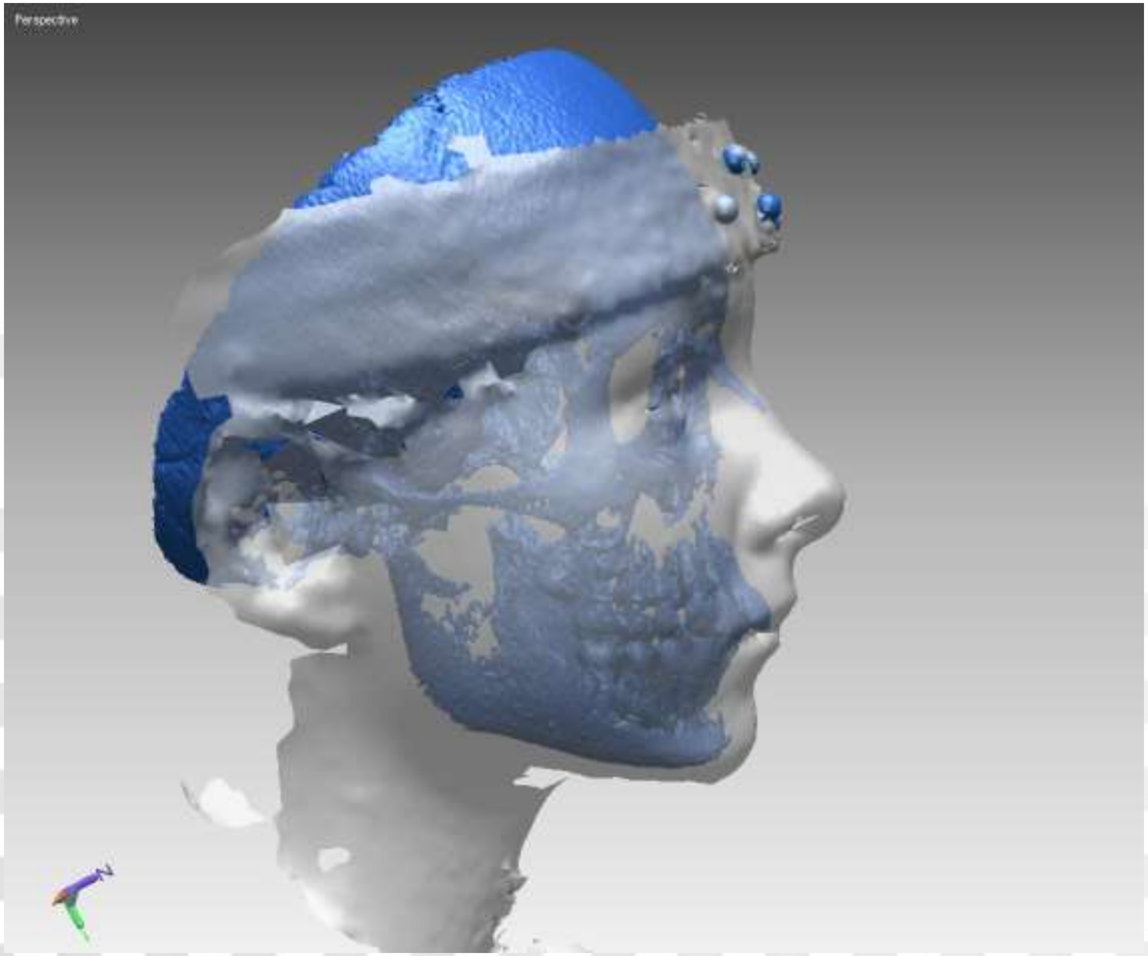
Patient 1 – 6months later Registration



Patient 2 – Time 0 Registration

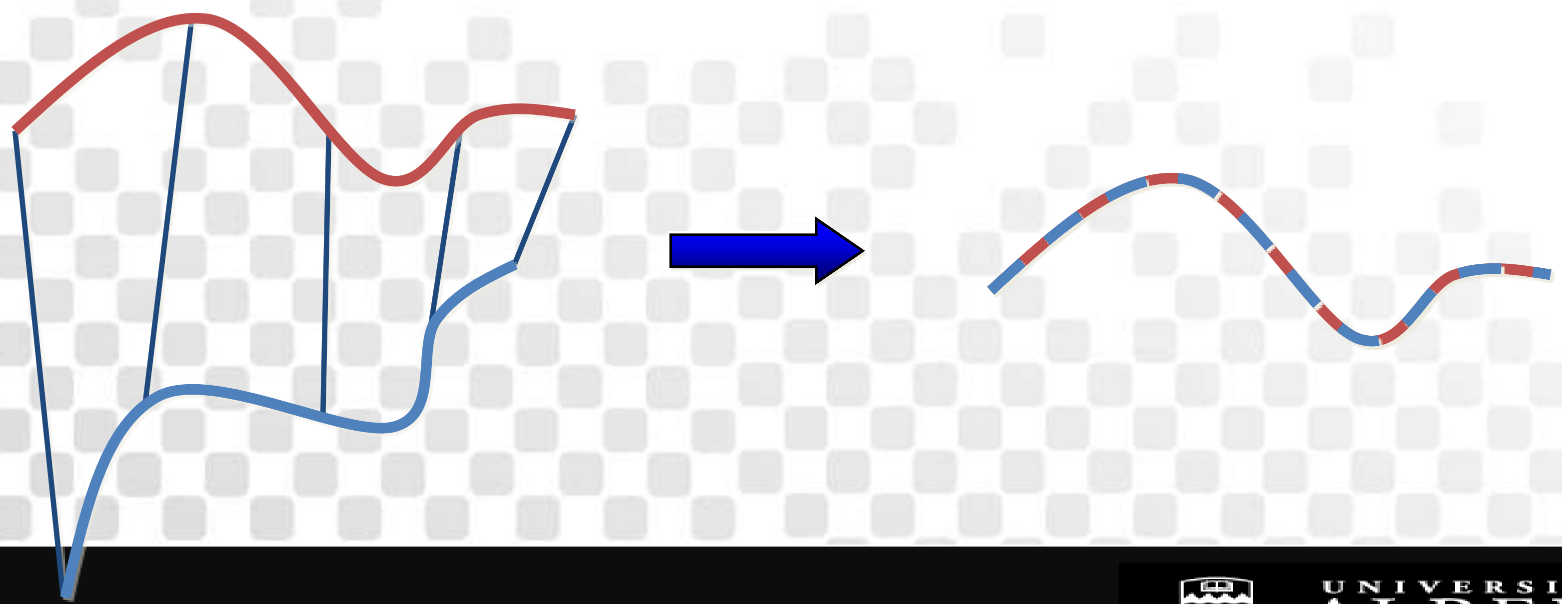


Patient 2 – 6months later Registration



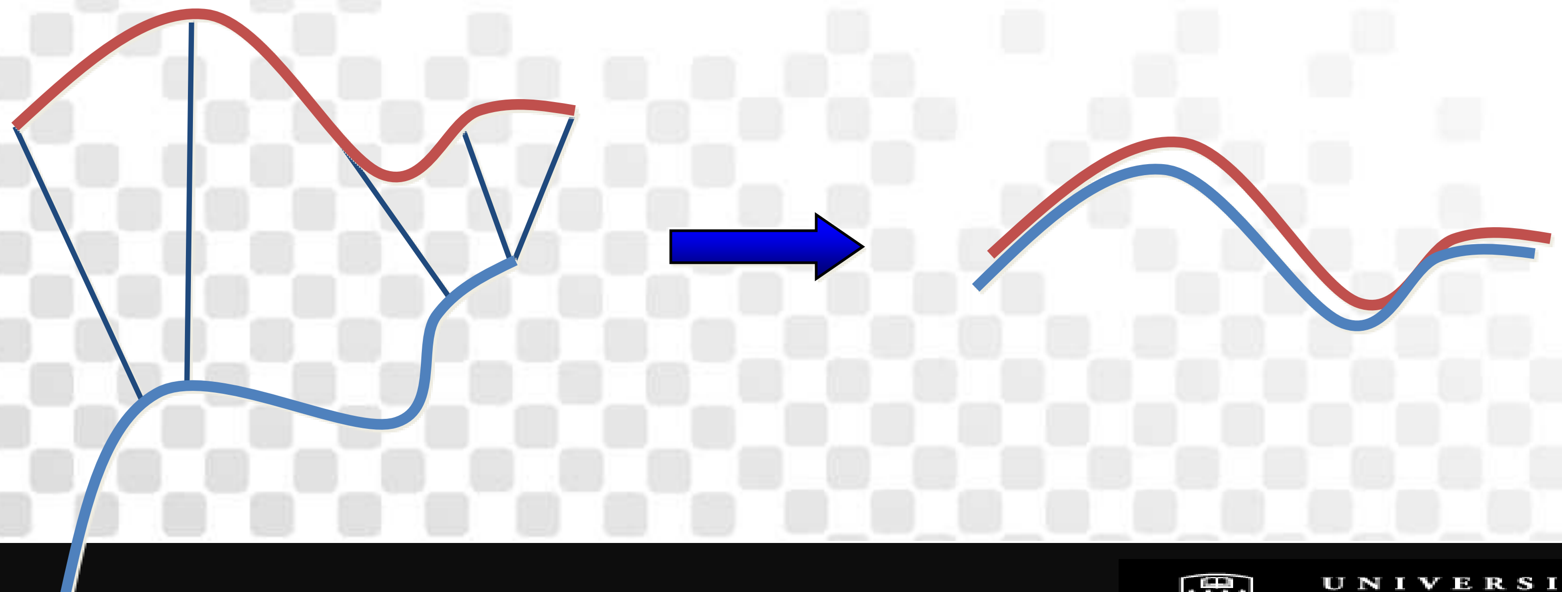
Rigid Registration(1)

If correct correspondences are known, one can find correct relative rotation/translation matrix directly



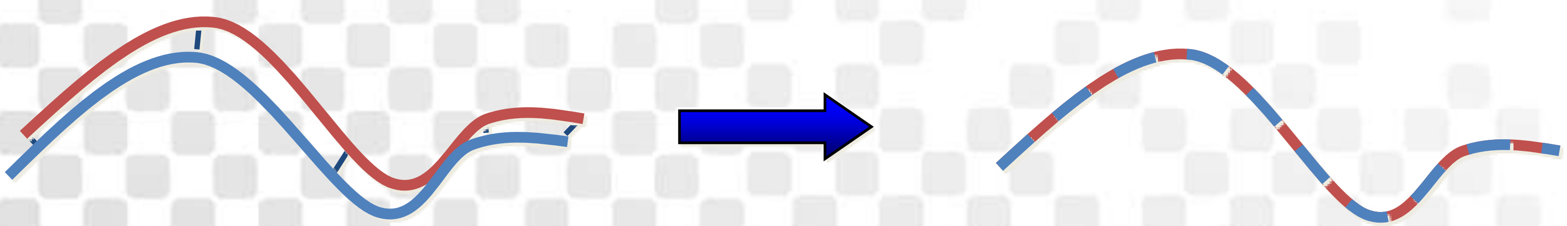
Rigid Registration(2)

- How to find correspondences: User input? Feature detection? Signatures? Landmarks?
- Alternative: assume closest points correspondence algorithm

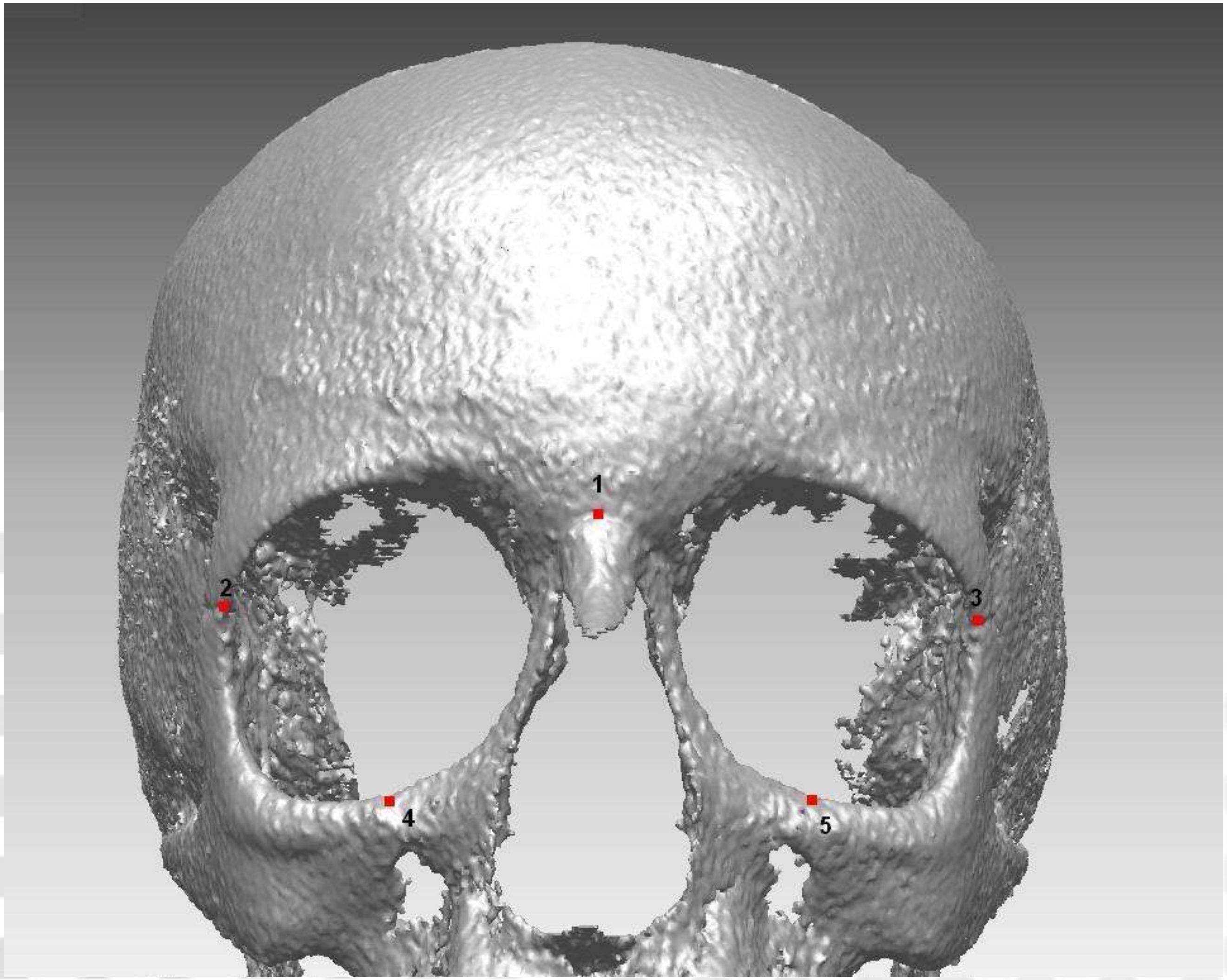


Rigid Registration(3)

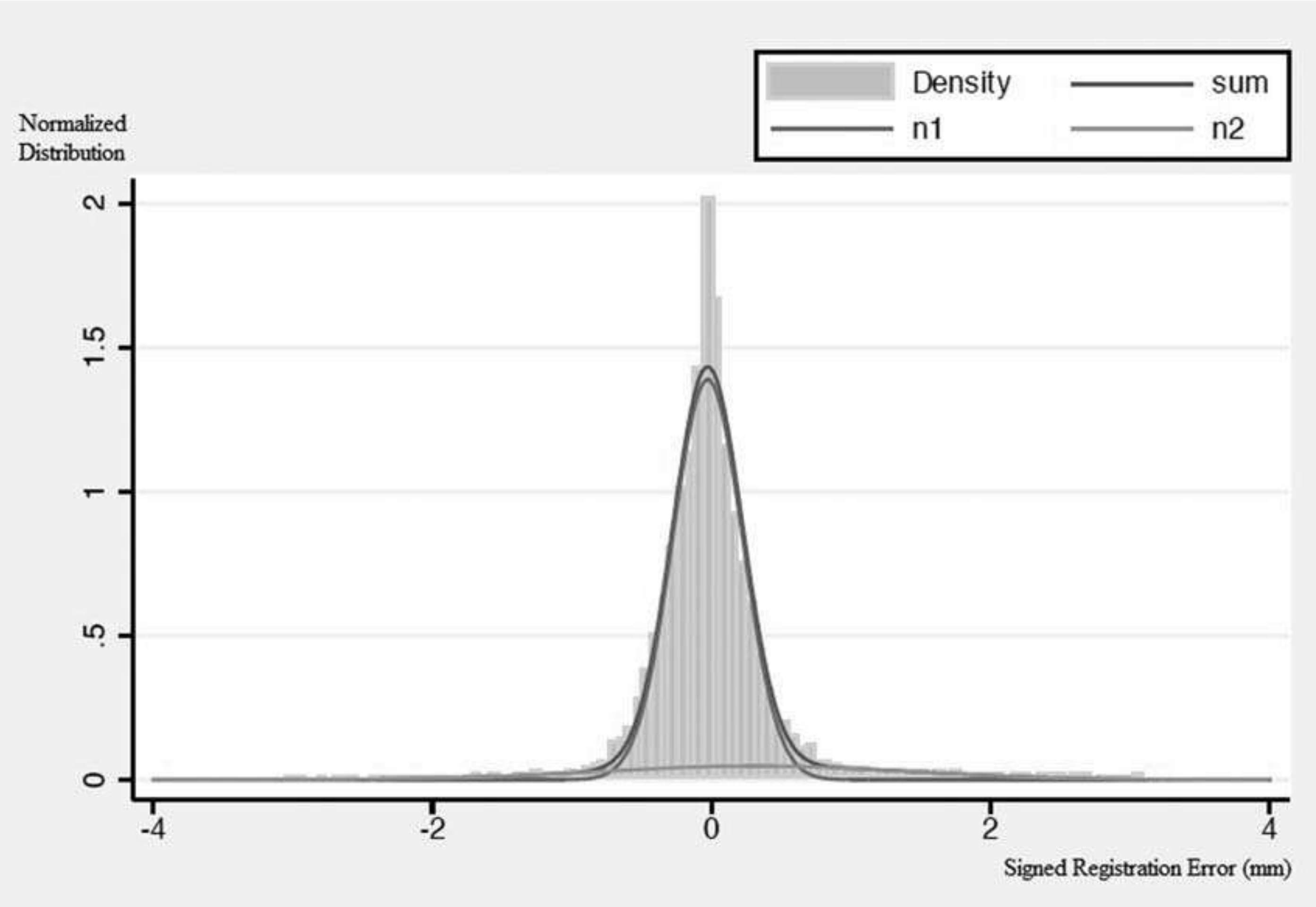
- … and iterate to find alignment
  - Iterative Closest Points (ICP) [Besl & McKay 92]
- Converges if starting position "close enough"



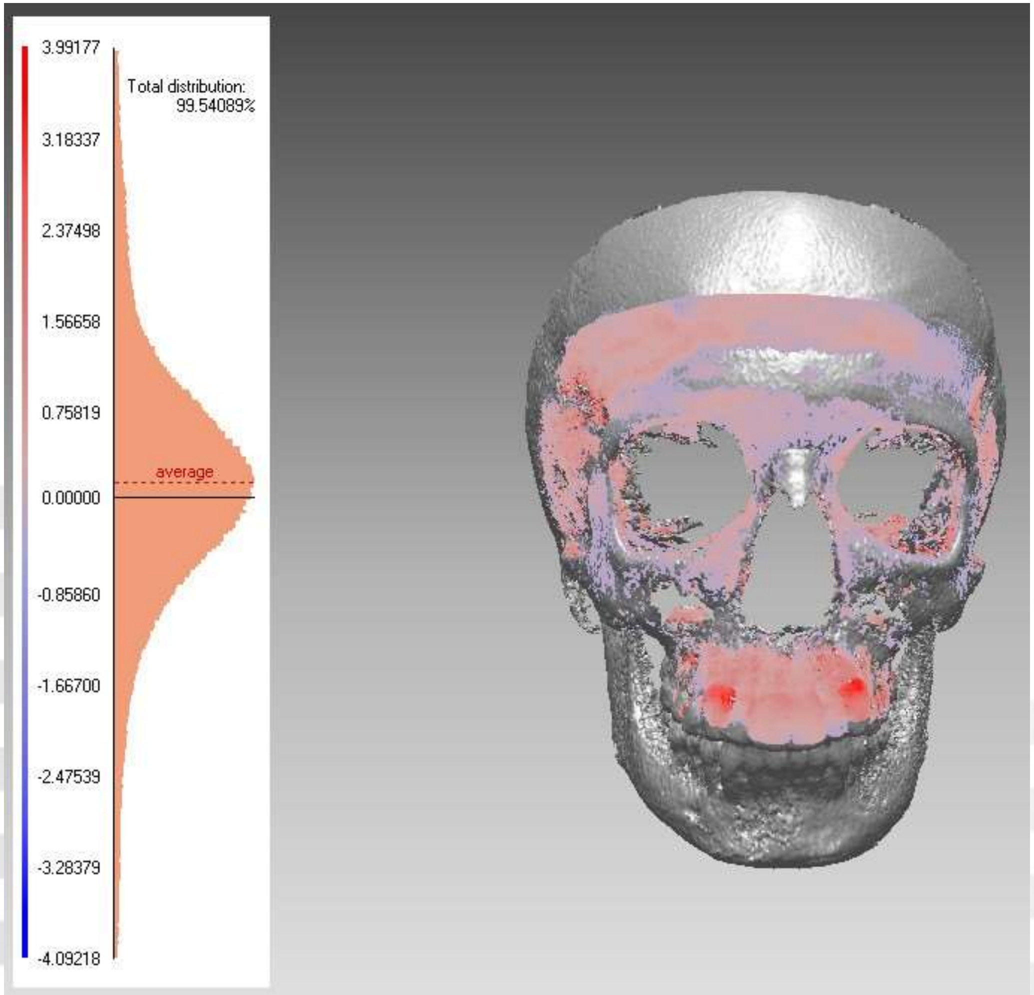
Natural Landmarks for Registration of Skulls through Time



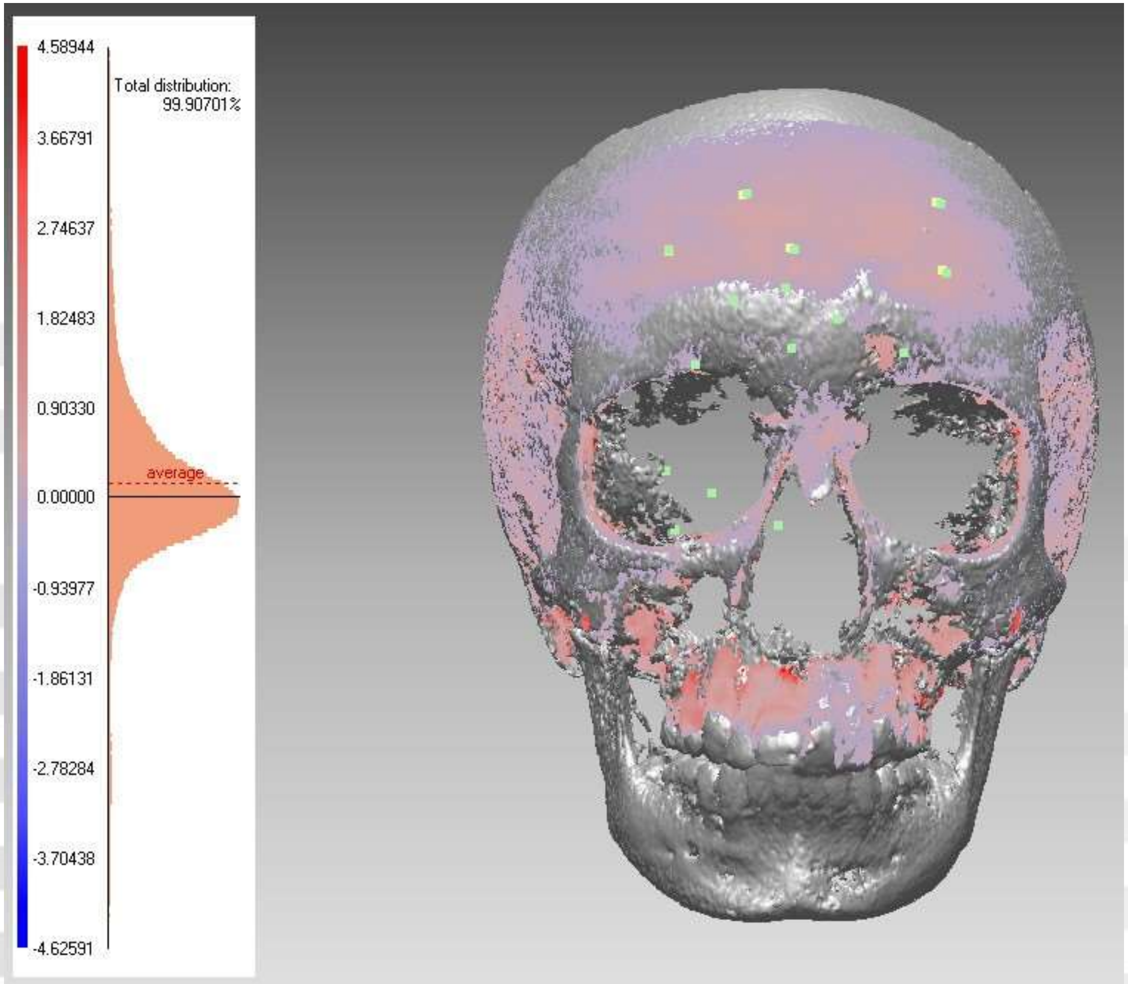
A Gaussian Mixture Model of Two Components Fitted on the Skull Data



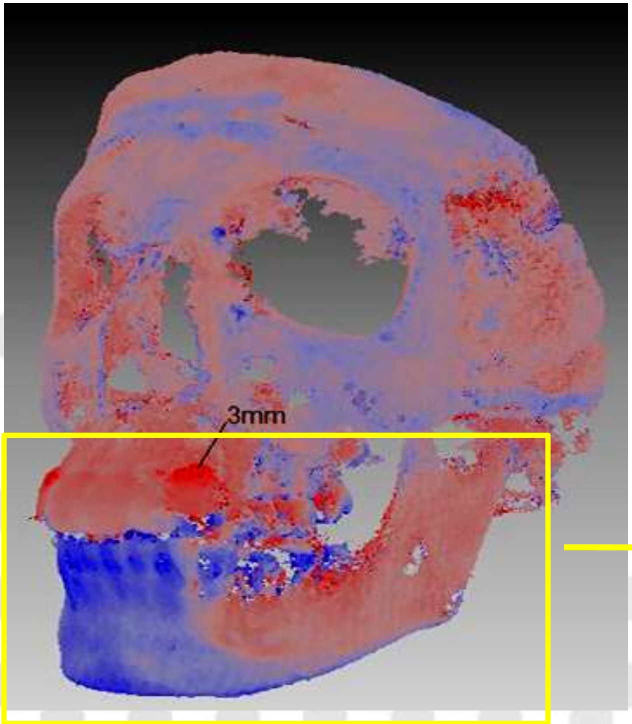
Patient 1 - Difference Map for Upper Skull

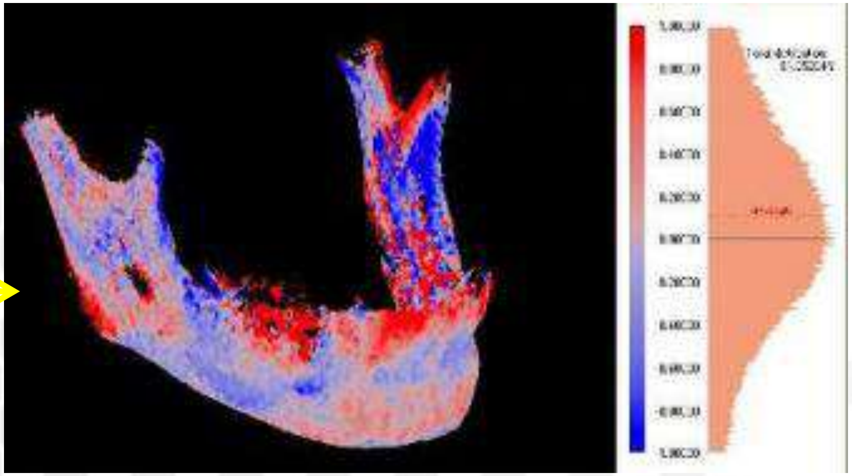


Patient 2 - Difference Map for Upper Skull

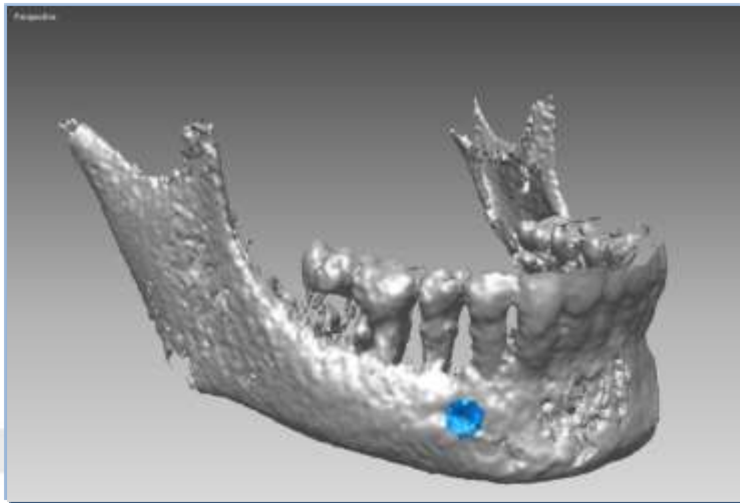


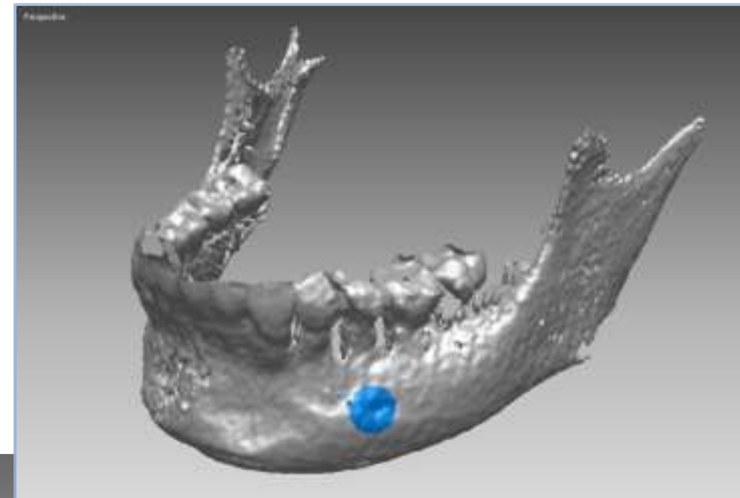
Lower Jaw Registration

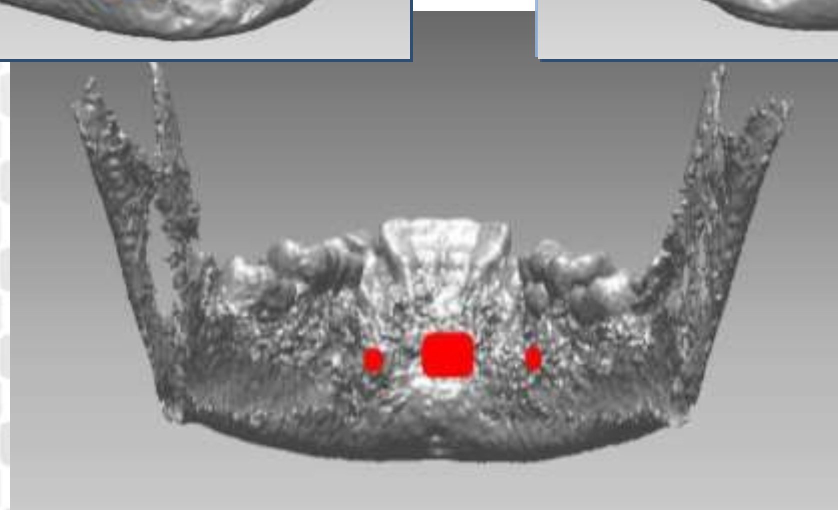




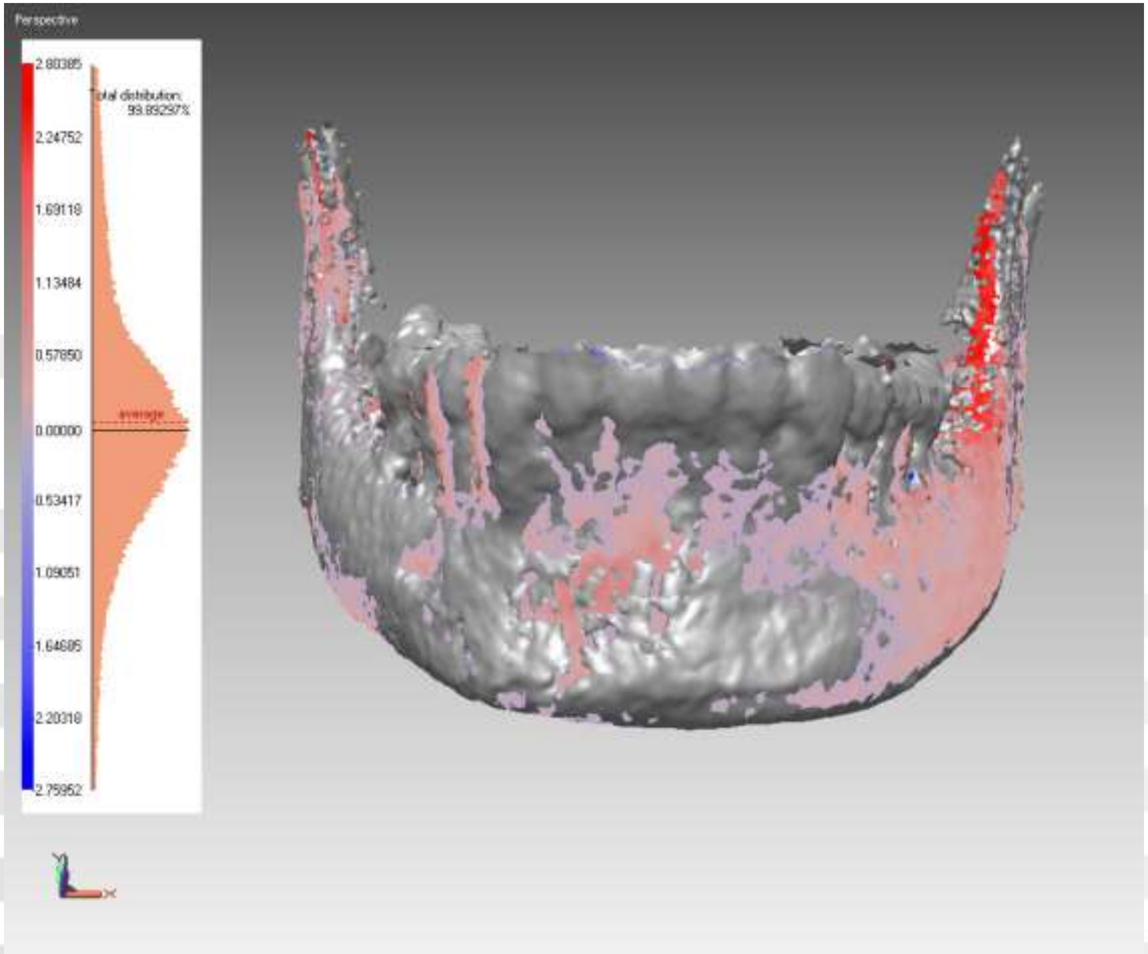
Natural Landmarks for Registration of Jaws through Time



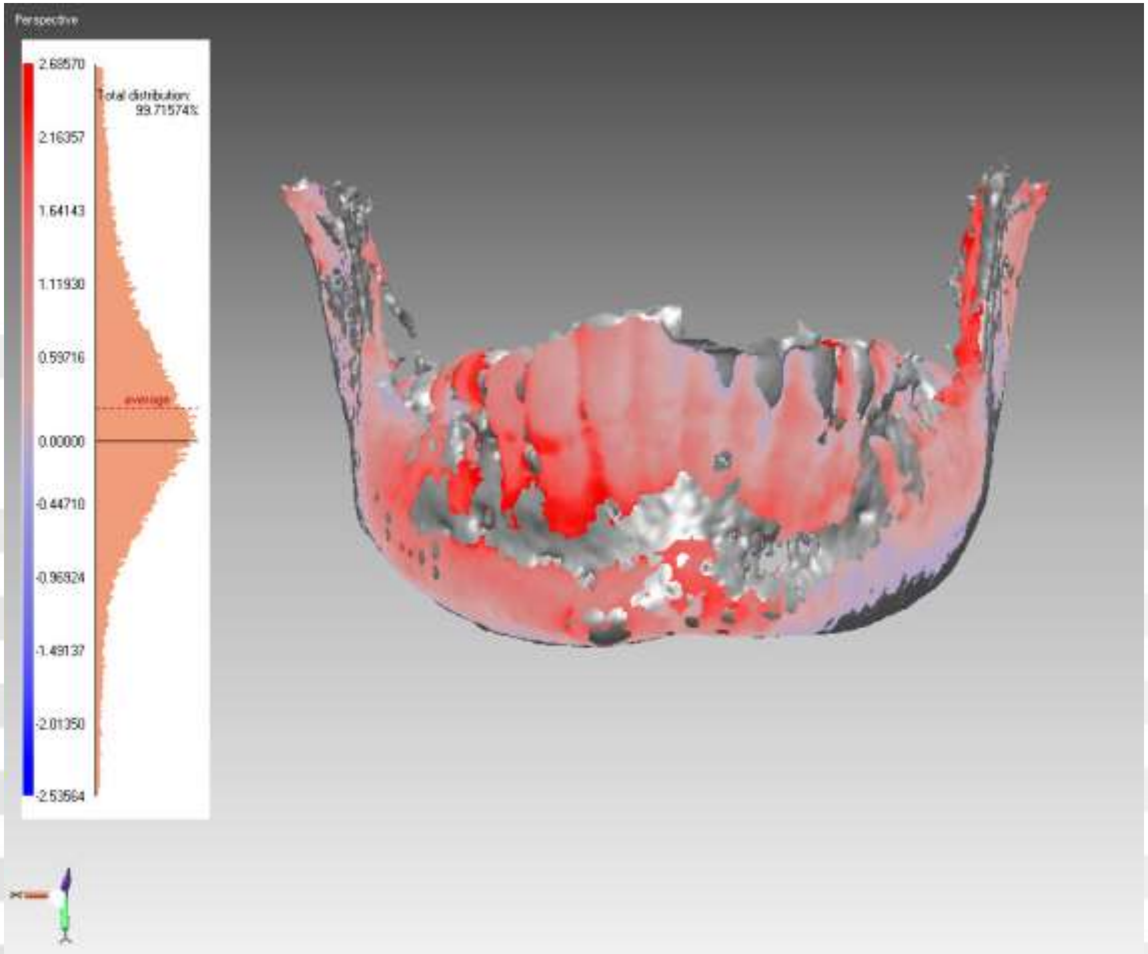




Patient 1 - Difference Map for Jaws



Patient 2 - Difference Map for Jaws



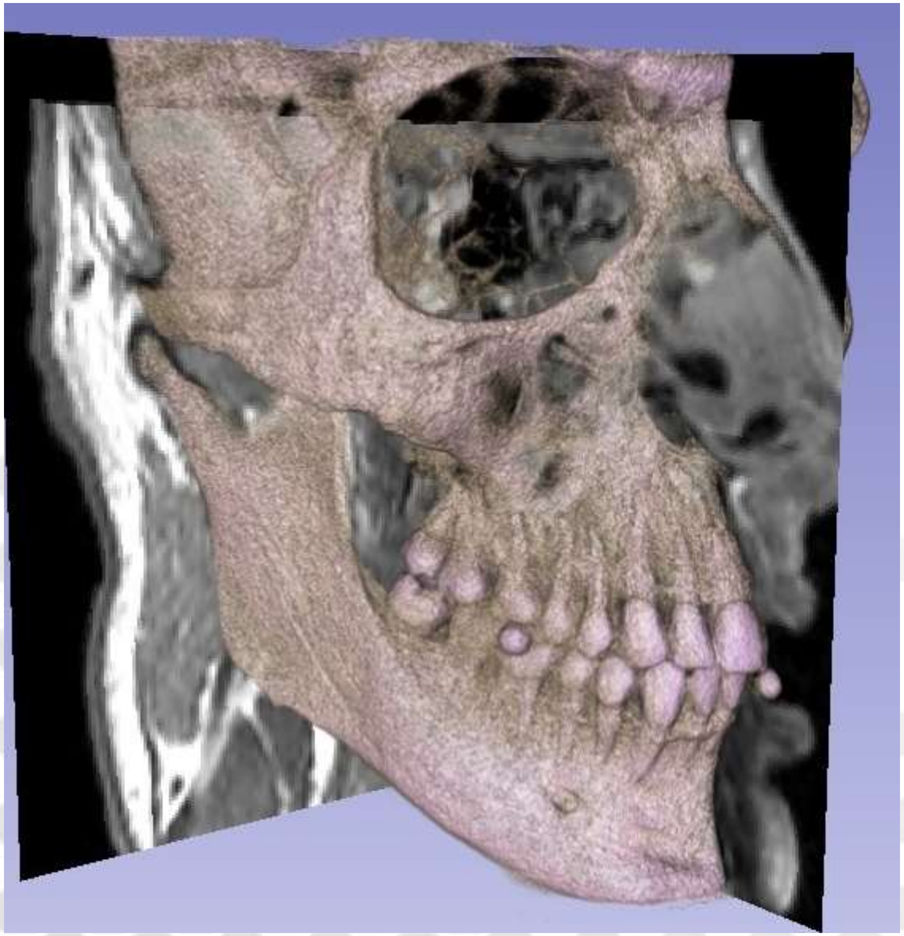
Registration for Tracking Treatment

Table 1 The normal distribution functions [formulated as N (μ, σ)] estimated for alignment errors and temporal change, extracted from the skull and the mandible signed errors

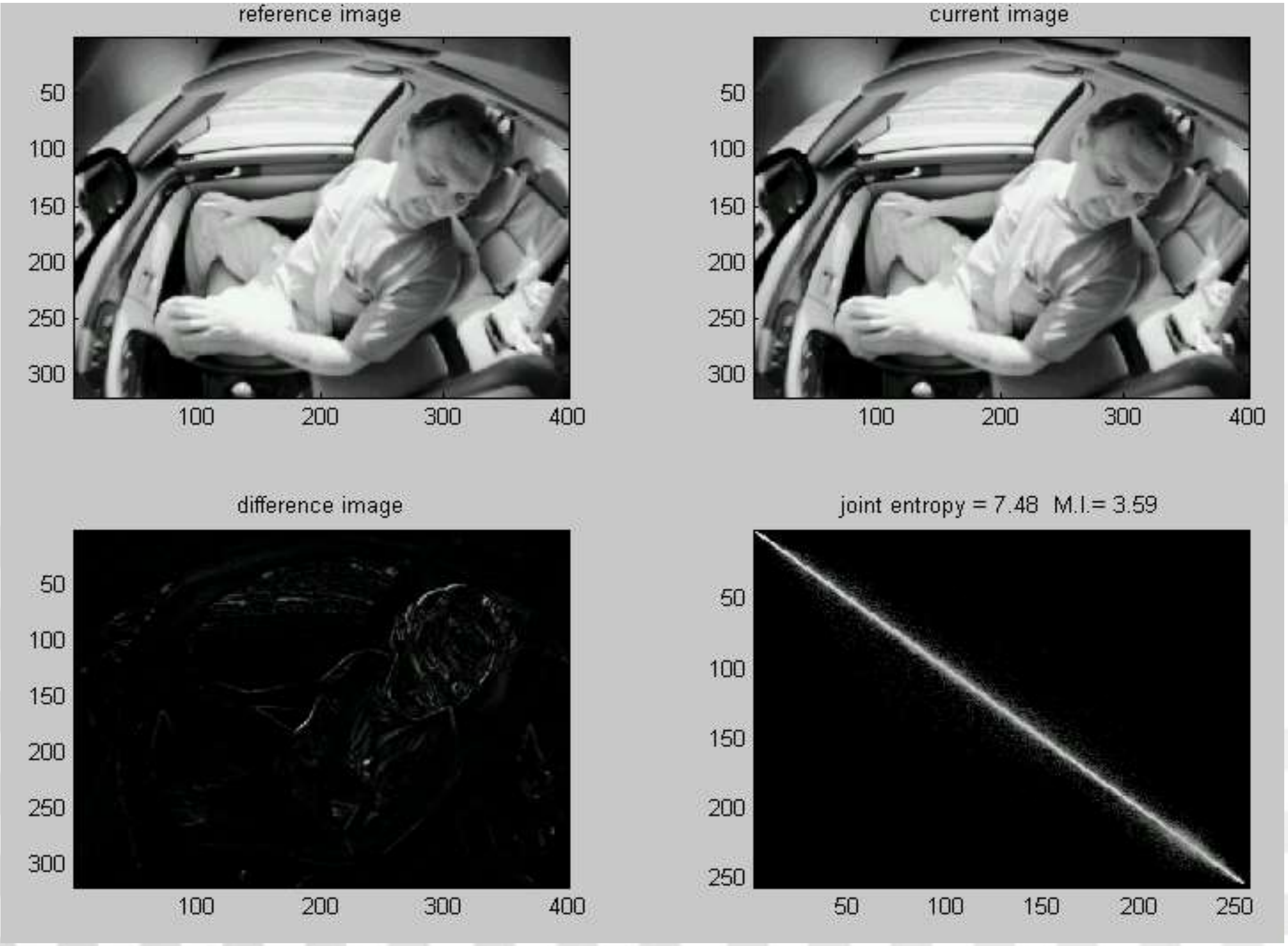
	Mandible alignment error	*Temporal change (between T1 and T2)*	*Skull alignment error*	*Temporal change (between T1 and T2)*
Subject 1 (treated)	N $(0.0032, 0.4444^2)$	N $(1.1799, 1.2044^2)$	N $(0.3772, 0.3175^2)$	N $(0.3772, 1.0251^2)$
Subject 2 (control)	N $(0.1510, 0.4871^2)$	N $(1.7621, 1.4257^2)$	N $(0.1606, 0.5205^2)$	N $(2.2225, 2.1840^2)$
Subject 3 (control)	N $(-0.0978, 0.4287^2)$	N $(0.0562, 1.3843^2)$	N $(-0.0177, 0.3289^2)$	N $(0.2161, 1.4472^2)$
Subject 4 (treated)	N$(-0.4517, 0.4891^2)$	N$(-1.3552, 1.4725^2)$	N$(-0.4768, 0.4802^2)$	N$(-0.4999, 1.6201^2)$
Subject 5 (control)	N $(0.0274, 0.4687^2)$	N $(1.1949, 1.6749^2)$	N $(0.0044, 0.2432^2)$	N $(0.4418, 1.6285^2)$
Subject 6 (treated)	N $(-0.1342, 0.4920^2)$	N $(1.1270, 2.3895^2)$	N $(-0.0273, 0.2521^2)$	N $(0.5246, 1.3304^2)$

All the measures are in millimetres.

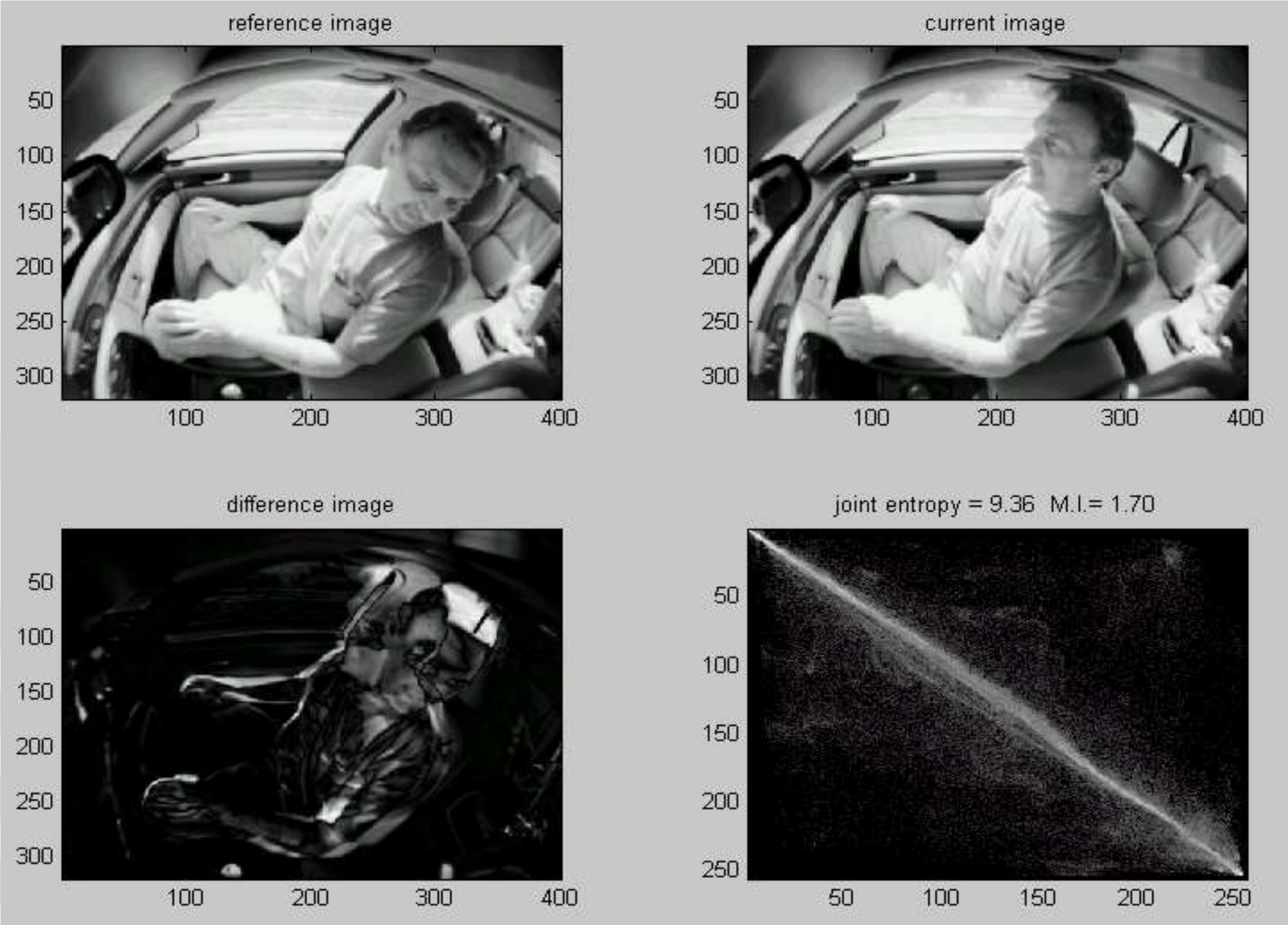
CBCT-MRI Registation



M.I. for Image Registration



M.I. for Image Registration



Definitions of Mutual Information

- **Three commonly used definitions:**
  - 1) $I(A,B) = H(B) - H(B|A) = H(A) - H(A|B)$
    - Mutual information is the amount that the uncertainty in B (or A) is reduced when A (or B) is known.
  - 2) $I(A,B) = H(A) + H(B) - H(A,B)$
    - Maximizing the mutual info is equivalent to minimizing the joint entropy (last term)
    - Advantage in using mutual info over joint entropy is it includes the individual input's entropy
    - Works better than simply joint entropy in regions of image background (low contrast) where there will be low joint entropy but this is offset by low individual entropies as well so the overall mutual information will be low

Definitions of Mutual Information

- 3) $$I(A,B) = \sum_{a,b} p(a,b) \cdot \log\left(\frac{p(a,b)}{p(a)\,p(b)} \right)$$

  - This definition is related to the Kullback-Leibler distance between two distributions
  - Measures the dependence of the two distributions
  - In image registration I(A,B) will be maximized when the images are aligned
  - In feature selection choose the features that minimize I(A,B) to ensure they are not related.

Additional Definitions of Mutual Information

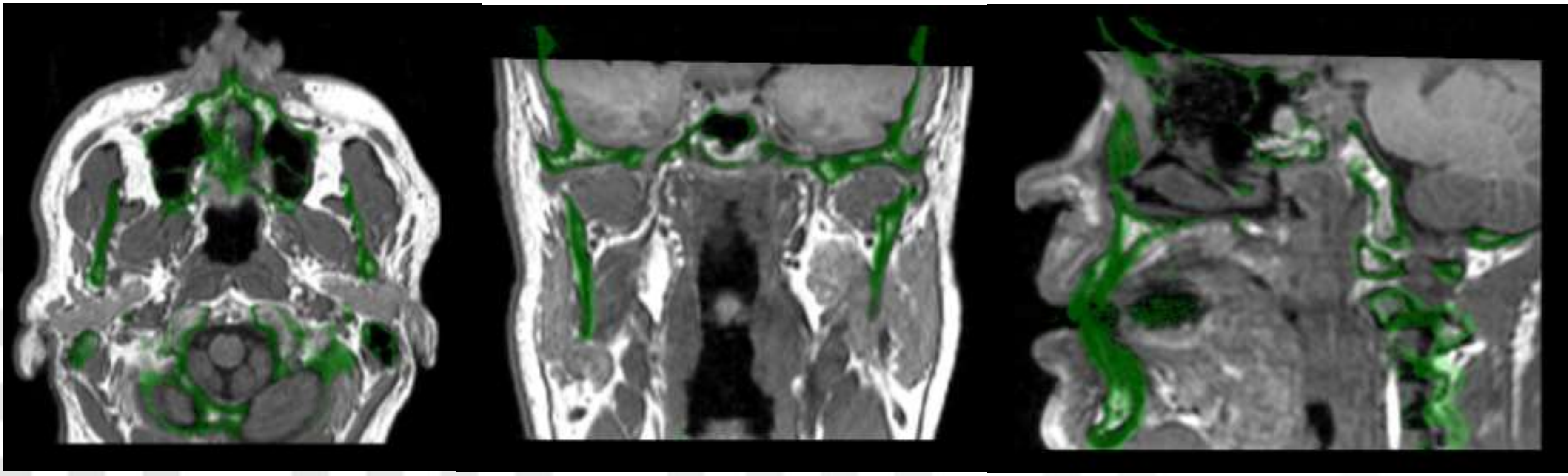
- **Two definitions exist for normalizing Mutual information:**
  - Normalized Mutual Information:

$$NMI(A,B) = \frac{H(A) + H(B)}{H(A,B)}$$

  - Entropy Correlation Coefficient:

$$ECC(A,B) = 2 - \frac{2}{NMI(A,B)}$$

CBCT-MRI Fusion Using Mutual Information Metric



Conclusion

- Our method produces alignment results of high accuracy and can thus be employed by dentists and physicians for tracking treatment results.
- We believe that a main source of outliers in our registration method is caused by segmentation.
- Further investigations on the effects of different isosurface values of the marching cubes algorithm may result in finding optimized values for registration.
- Using Mutual Information may solve this problem