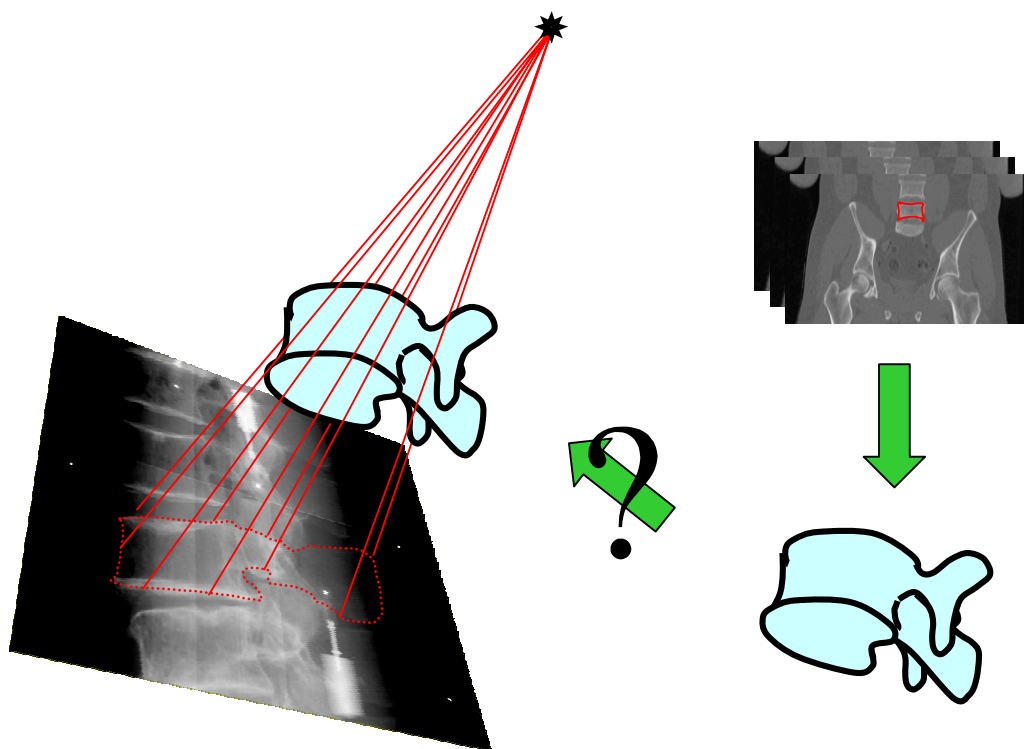


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# *Gold standard data for evaluation of 2D-3D registration*

## **User's Guide**

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The all rights to gold standard data posses the Laboratory of Imaging Technologies. The non-authorized distribution of this data is strictly forbidden. This gold standard data can only be obtained and used after signing the agreement form between the user and Imaging Technologies Laboratory.

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## 1. INTRODUCTION

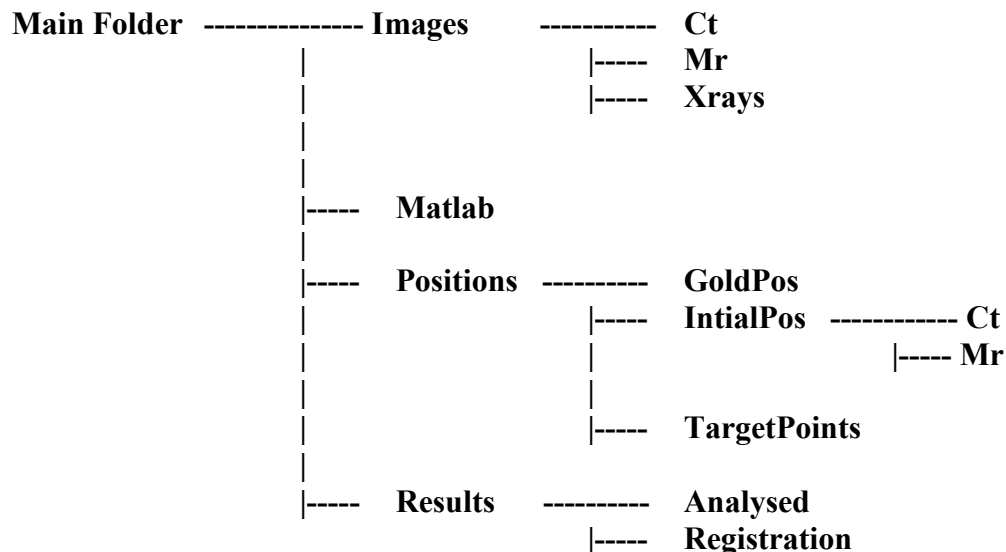
Validation of 2D/3D registration techniques needed for image-guided surgery is an important problem, which received little attention in the literature. One difficulty in evaluating a registration technique is the need for highly accurate gold standard. Several researchers have addressed the validation problem in the context of particular methods, but their results cannot be directly compared because they used different image data and different methodology for validation. The situation in this research field calls for a public available gold standard data and a standard methodology to assess the accuracy and reliability of the registration methods proposed by different researchers.

For this purpose we have devised a cadaveric lumbar spine phantom with fiducial markers and established highly accurate correspondence between 3D CT and MR images and 18 2D X-ray images of the phantom [1]. The expected target registration errors are in the order of 0.2 mm for CT to X-ray registration and in the order of 0.3 mm for MR to X-ray registration. The CT, MR and X-ray images, gold standard registration, and Matlab source code for registration evaluation can be obtained on request from the authors.

## 2. DATA

### 2.1 CONTENTS

The gold standard data has the following folder structure:



## 2.2 X – RAY DATA

The X-ray data is comprised of 18 X-ray images which are located in the folder `.\Images\Xrays\`. Each X-ray image consists of two files, the header file `imXXX.rad` and the raw data file `imXXX.raw`. The header file is written in ASCII format and can be opened with any text editor. The items in the header file are

```
Size[pixels]:  $N_x N_y$ 
Step[mm]:  $\Delta x \Delta y$ 
DataType: float
TPosition:
  nx sx ax tx
  ny sy ay ty
  nz sz az tz
  0 0 0 1
SourcePosition[mm]:  $x_s y_s z_s$ 
```

where  $N_x$  and  $N_y$  are sizes of X-ray image in pixels, the  $\Delta x$  and  $\Delta y$  are the sizes of each pixel in millimeters, the feature `DataType: float` informs that raw file is written in float format, the numbers after the `TPosition:` presents the rigid transformation matrix

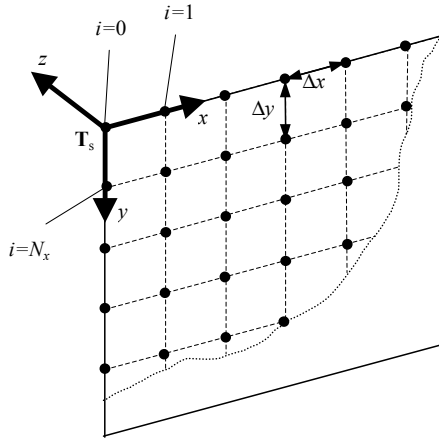
$$\mathbf{T}_s = \begin{bmatrix} nx & sx & ax & tx \\ ny & sy & ay & ty \\ nz & sz & az & tz \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

defining the position of X-ray sensor in the reference coordinate system, and the  $x_s, y_s$  and  $z_s$  stands for the position of the X-ray source in the reference coordinate system.

The raw file is comprised of  $N_x * N_y$  **float** values presenting the X-ray image intensities (Note that the intensity range of X-ray images is large and that the best range to observe the vertebra bone is 0-110). The offset  $i$  for a given pixel's intensity value in the raw data is defined as

$$i = i_x + N_x \cdot i_y$$

where  $i_x$  and  $i_y$  are integer values presenting pixel's position on the image grid (Fig. 1).



**Fig. 1** The coordinate system of the X-ray image.

### 2.3 CT AND MR DATA

The CT and MR data are located in the folders `.\Images\Ct\` and `.\Images\Mr\`. Each folder consists of five volumes presenting vertebrae L1-L5. Each volume is comprised of two files, the header file `LX.sta` and the raw data file `LX.raw`. The header file is ASCII file with following items

```
Size[pixels]:  $N_x N_y N_z$ 
Step[mm]:  $\Delta x \Delta y \Delta z$ 
DataType: uint8
TPosition:
nx sx ax tx
ny sy ay ty
nz sz az tz
0 0 0 1
```

where  $N_x$ ,  $N_y$ , and  $N_z$  are sizes of volume in voxels, the  $\Delta x$ ,  $\Delta y$  and  $\Delta z$  are the sizes of each voxel in millimeters, the feature `DataType: uint8` informs that raw file is written in unsigned 8 bit format and numbers after the `TPosition:` presents the rigid transformation matrix

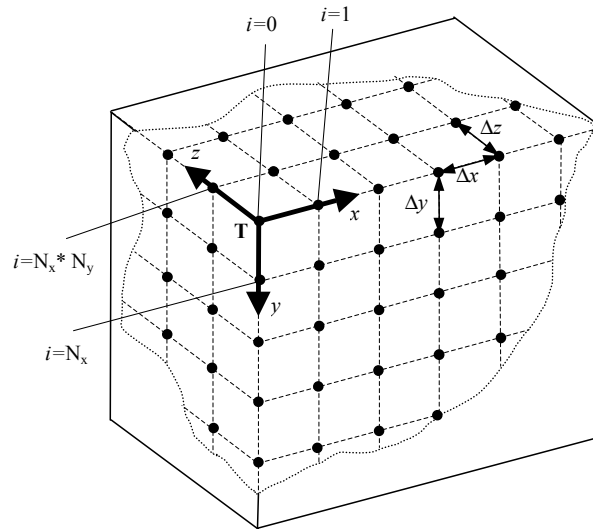
$$\mathbf{T} = \begin{bmatrix} nx & sx & ax & tx \\ ny & sy & ay & ty \\ nz & sz & az & tz \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

defining the position of volume in the reference coordinate system.

The raw file is comprised of  $N_x \cdot N_y \cdot N_z$  **unsigned 8 bit** values presenting volume intensities. The offset  $i$  for a given voxel's intensity value in the raw data is calculated as

$$i = i_x + N_x \cdot i_y + N_x \cdot N_y \cdot i_z$$

where  $i_x$ ,  $i_y$  and  $i_z$  are integer values presenting voxel's position on the volume grid (Fig. 2).



**Fig. 2** The coordinate system of the CT and MR volume.

## 2.4 GOLD STANDARD REGISTRATION

The folder `.\Positions\GoldPos\` contains files `gold_ctLX.txt` and `gold_mrLX.txt` defining gold standard registration for each CT and MR volume. Each file is written in ASCII format and contains gold standard rigid transformation matrix  $T_g$  of size 4x4.

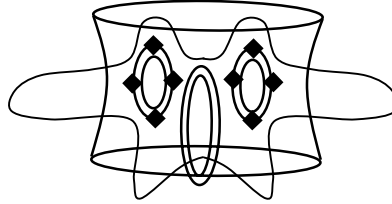
## 2.5 TARGET POINTS

The folder `.\Positions\TargetPoints\` consists of files `TpointsLX.txt` and `CpointLX.txt`. Each file `TpointsLX.txt` is written in ASCII format and contains matrix of size 8x3 defining eight target points  $p_t$  described in the coordinate system of the CT data. The target points were manually placed at pedicle borders (see Fig. 3) and are used to calculate a target registration error (TRE) [2] which is defined as

$$TRE(p_i) = \|T_t p_i - T_g p_i\|$$



where  $\mathbf{T}_g$  and  $\mathbf{T}_r$  are rigid transformations presenting gold standard volume position and position obtained by the registration method, respectively.



**Fig. 3** Positions of eight target points (◆) defining pedicle borders.

Each file **CpointLX.txt** consists of single point  $\mathbf{p}_t$  presenting center of each vertebra L1-L5 defined in the coordinate system of CT volume.

**Note:** The center points are used to calculate the normalized distance from the gold standard registration

$$d_{norm} = \sqrt{a^2 + b^2}$$

where

$$a = TRE(\mathbf{p}_t)$$

$$b = k \cdot \gamma$$

and  $\gamma$  stands for angle error [3,4] and  $k$  is normalization constant ( $k=20$  mm/rad).

## 2.6 INITIAL DISPLACEMENTS

The folders `.\Positions\IntialPos\Ct\` and `.\Positions\IntialPos\Mr\` provide the information for the standardized registration experiment. Each file **start\_ctLX.txt** or **start\_mrLX.txt** consists of the matrix  $\mathbf{X}_S$  of size 1800x4. The matrix contains of 450 initial vertebra displacements given by the rigid transformation matrix  $\mathbf{T}_j$  of size 4x4

$$\mathbf{X}_S = \begin{bmatrix} \mathbf{T}_1 \\ \vdots \\ \mathbf{T}_{450} \end{bmatrix}$$

Each file `rad_ctLX.txt` and `rad_mrLX.txt` consist of a matrix  $\mathbf{X}_S$  of size 450x2, where line  $j$  in the matrix  $\mathbf{X}_S$  contains the indexes of two X-ray images that are used for the registration of each vertebra with initial displacement  $\mathbf{T}_j$ .

**Note:** The initial displacements with given X-ray images were used for testing registration method proposed by Tomazevic *et. al* [4]. The authors encourage the users of gold standard data to use the same initial displacements and the same X-ray images in their registration experiments. Only this kind of standardized experiment can provide comparable registration results of different registration methods.

## 2.7 REGISTRATION RESULTS

In order to analyze the registration results by Matlab source code the results per each vertebra should be given in the files `reg_ctLX.txt` or `reg_mrLX.txt`. In general, each file should consist of matrix  $\mathbf{X}_R$  of size  $(N*4) \times 4$ , where  $N$  is a number of registrations per each vertebrae. The matrix  $\mathbf{X}_R$  comprises  $N$  rigid transformation matrix  $\mathbf{T}_j$  of size  $4 \times 4$ , where each matrix  $\mathbf{T}_j$  presents the vertebra position obtained by  $j$ -th registration

$$\mathbf{X}_R = \begin{bmatrix} \mathbf{T}_1 \\ \vdots \\ \mathbf{T}_N \end{bmatrix}$$

Furthermore, the initial vertebrae displacements for each vertebra should be provided in the files `start_ctLX.txt` or `star_mrLX.txt` in order to obtain capturing range of the registration method, where each file consists of matrix  $\mathbf{X}_S$ , that comprises  $N$  initial displacements  $\mathbf{T}_j$

$$\mathbf{X}_S = \begin{bmatrix} \mathbf{T}_1 \\ \vdots \\ \mathbf{T}_N \end{bmatrix}$$

In the folder `.\Results\Registration\` an example of registration results obtained by method proposed by Tomazevic *et. al* [4] are given. The initial displacements and X-ray images that were used in the registration experiment are provided in the folders `.\Positions\IntialPos\Ct\` and `.\Positions\IntialPos\Mr\`.

## 3. ANALYSING REGISTRTION RESULTS

The Matlab source code for analyzing registration results is provided in the folder `.\Matlab\`. The prescribed format of registration results is given in Chapter 2.7.

### 3.1 ANALYZING RESULTS FOR VERTEBRAE L1-L5

Functions `analyse_all_CT` and `analyse_all_MR` analyze the registration results for vertebrae L1-L5 for CT and MR images, respectively. These two functions are used as

```
[ALL_Results, Converg_Curve ]
    = analyse_all_XX(RegResults_Folder,AnalysedResults_Folder)
```

where `RegResults_Folder` ( [] for default `.\Results\Registration\`) stands for the folder containing results obtained by registration experiment (see Chapter 2.7) and `AnalysedResults_Folder` ( [] for default `.\Results\Analysed\`) stands for the folder for result of analysis.

The result matrix `ALL_Results` is of size 11x6 and contains the obtained registration errors and proportion of successful registrations, where matrix `Converg_Curve` is of size 9x2 and returns curve that presents effect of initial displacement on probability of successful registration. The description of the matrix elements `ALL_Results` is given in Table 1 and Table 2, for the CT and MR data respectively, while the examples of `Converg_Curve` are given in Fig. 4. Both Table 1 and Table 2 give the root mean squares and maximum values of TRE and rotation error  $\gamma$  before and after registration. Only before and after registration errors for successful registrations are given. The tables also give the proportion of successful registrations for different intervals of initial displacements.

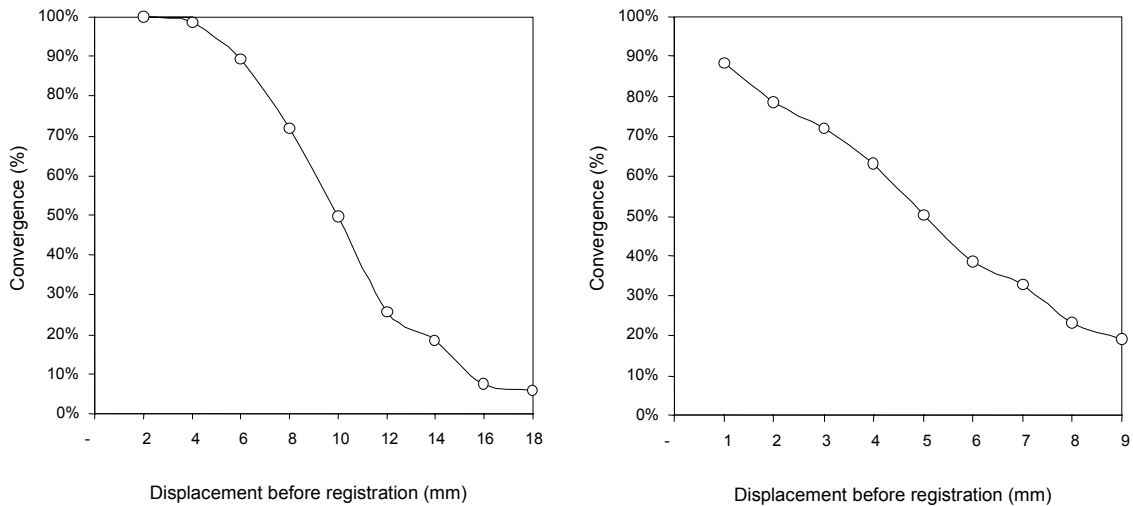
Furthermore, the functions `analyse_all_CT` and `analyse_all_MR` saves result of analysis (`ALL_Results` and `Converg_Curve` matrix) in the folder `AnalysedResults_Folder` as files `XX_results_all.txt` and `XX_converg_all.txt`.

**Table 1** The example of result for CT to X-ray registration obtained in the matrix `ALL_Results`.

	Before registration				After registration				Successful registrations (%)		
	Rms(TRE) (mm)	Max(TRE) (mm)	Rms( $\theta$ ) ( $^{\circ}$ )	Max( $\theta$ ) ( $^{\circ}$ )	Rms(TRE) (mm)	Max(TRE) (mm)	Rms( $\theta$ ) ( $^{\circ}$ )	Max( $\theta$ ) ( $^{\circ}$ )	0÷6mm 0÷17.2 $^{\circ}$	6÷12mm 17.2÷34.4 $^{\circ}$	12÷18mm 34.4÷51.7 $^{\circ}$
L1	5.95	21.42	13.34	37.43	0.40	1.59	0.37	0.94	96.7	50.7	11.6
L2	5.55	19.71	12.03	37.82	0.30	0.59	0.41	0.79	94.7	43.3	6.2
L3	6.09	21.07	13.83	36.06	0.22	0.46	0.35	0.67	94.7	51.3	14.4
L4	6.02	20.12	13.30	49.04	0.24	0.46	0.32	0.62	92.1	41.3	10.3
L5	6.66	25.91	14.44	52.04	0.49	0.77	0.34	0.82	94.7	52.0	13.7
All	6.07	25.91	13.44	52.04	0.35	1.59	0.36	0.94	94.6	47.7	11.2

**Table 2** The example of result for MR to X-ray registration obtained in the matrix ALL\_Results.

	Before registration				After registration				Successful registrations (%)		
	Rms(TRE) (mm)	Max(TRE) (mm)	Rms( $\theta$ ) ( $^\circ$ )	Max( $\theta$ ) ( $^\circ$ )	Rms(TRE) (mm)	Max(TRE) (mm)	Rms( $\theta$ ) ( $^\circ$ )	Max( $\theta$ ) ( $^\circ$ )	0 $\pm$ 3mm 0 $\pm$ 8.6 $^\circ$	3 $\pm$ 6mm 8.6 $\pm$ 17.2 $^\circ$	6 $\pm$ 9mm 17.2 $\pm$ 25.8 $^\circ$
L1	3.82	11.67	8.19	20.42	1.43	2.00	1.65	4.74	50.0	36.7	19.0
L2	3.64	10.91	7.75	24.40	1.36	1.99	1.73	4.18	83.4	55.0	23.8
L3	3.52	11.80	8.10	24.56	1.15	1.99	1.51	4.71	82.7	48.7	25.2
L4	3.43	11.18	7.43	25.81	1.09	1.71	1.11	2.01	89.3	44.3	16.2
L5	4.03	13.60	8.39	22.12	1.23	1.99	1.04	1.80	86.8	59.7	34.7
All	3.70	13.60	7.98	25.81	1.25	2.00	1.41	4.74	78.5	48.9	23.8



**Fig. 4** The effect of initial displacement on proportion of successful registrations given by Converg\_Curve for CT (left) and MR(right) data.

### 3.2 ANALYZING RESULTS FOR SINGLE VERTEBRA

Functions analyse\_single\_CT and analyse\_single\_MR analyze the registration results for single vertebra. These two functions are used as

```
[Results, Converg_Curve, TREs ]=
    analyse_single_MR(Vertebra,RegResults_Folder,
        AnalysedResults_Folder)
```

where `Vertebra` stands for vertebra `'L1'`, `'L2'`,..., `'L5'` to analyze, and `RegResults_Folder` ([] for default `.\Results\Registration\`) stands for the folder containing results obtained by registration experiment and `AnalysedResults_Folder` ([] for default `.\Results\Analysed\`) stands for the folder for result of analysis.

The result vector `Results` is of size  $11 \times 1$  and contains registration results for single vertebra (see Table 1 and Table 2). The matrix `Converg_Curve` is of size  $9 \times 2$  and returns the convergence curve (see Fig. 4). The result matrix `TREs` is of size  $N \times 8$ , where  $N$  is a number of registrations, where  $j$ -th line in the matrix stands for TRE of 8 target points (see Fig. 3) for  $j$ -th registration.

The functions `analyse_single_CT` and `analyse_single_MR` save result of analyze (`ALL_Results`, `Converg_Curve` and `TREs` matrix) in the folder `AnalysedResults_Folder` as files `XX_results_single_LX.txt`, `XX_converg_single_LX.txt` and `CT_TREs_single_LX.txt`.

## 4. REFERENCES

- [1] D. Tomaževič, B. Likar, F. Pernuš, "Gold Standard 2D/3D Registration of X-ray to CT and MR Images", MICCAI 2002, *In press*.
- [2] J. M. Fitzpatrick, J. B. West, and C. R. Maurer, "Predicting Error in Rigid-Body Point-Based Registration," *IEEE Transactions on Medical Imaging*, vol. 17, pp. 694-702, 1998.
- [3] D. Tomaževič, *2D/3D registration of medical images*, Master's Thesis at University of Ljubljana, 2002.
- [4] D. Tomaževič, B. Likar, F. Pernuš, "Rigid 2D/3D registration of intraoperative digital X-ray images and preoperative CT and MR images", In: *Proceeding of Medical Imaging 2002*, M. Sonka and J.M. Fitzpatrick, SPIE Press 4684:507-517, 2002.