

A NEW SYMMETRY-BASED METHOD FOR MID-SAGITTAL PLANE EXTRACTION IN NEUROIMAGES

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ABSTRACT

The estimation of the mid-sagittal plane (MSP) is a known problem with several applications in neuroimage analysis. As advance to the state-of-the-art, we present a considerably better approach for MSP extraction based on bilateral symmetry maximization and a more suitable error metric to compare MSP estimation methods. The proposed method was quantitatively evaluated using three other state-of-the-art approaches as baselines and a heterogeneous dataset with 164 clinical images. It outperformed the others in accuracy and precision, being well succeeded on all images. Besides, it does not present limitations with respect to the imaging protocol and initial position of the head, and it is one of the fastest methods in the literature, taking around 30 seconds on a regular workstation.

Index Terms— mid-sagittal plane extraction, symmetry quantification, neuroimage registration, medical image analysis

1. INTRODUCTION

The human brain can be divided into two hemispheres with an approximate bilateral symmetry, where most structures in one side have a corresponding counterpart on the other side with similar shape and relative location. The two hemispheres can be distinguished visually by the longitudinal fissure, which is a membrane between the left and right hemispheres filled with cerebro-spinal fluid (CSF). Thus, the separation of the hemispheres in the image can be done by defining a mid-sagittal plane (MSP) along the longitudinal fissure. Actually, the separation surface is usually curved, mainly in the case of patients, but the planar approximation is sufficient for several applications involving registration and asymmetry analysis (e.g., segmentation of focal cortical dysplasia in epilepsy [1] and discovery of biomarkers in Alzheimer disease [2, 3]).

MSP extraction methods can be divided in two groups: (i) methods that define the MSP as a plane which maximizes a symmetry measure, extracted from both sides of this plane [4, 5, 6, 7, 8], and (ii) methods that detect the location of the longitudinal fissure to estimate the MSP [9, 10, 11, 12]. Extensive reviews on these methods can be found in [5, 12, 10, 6].

Methods from the second group are suitable for MR images, where the longitudinal fissure appears clearly. However, they present limitations and/or disadvantages in several other cases. In SPECT

and PET images, for example, the fissure is not visible and, in CT images, the fissure is not well defined as in MR images. Besides, in pathological cases involving the presence of tumors, one side can compress the other side of the brain, making the fissure very curved to adjust a good plane. On the other hand, methods from the first group only assume some degree of symmetry between the left and right hemispheres. Even in the case of very curved fissures, this can be valid for the rest of the image. In this sense, the methods from the first group are more suitable for all imaging protocols.

Despite the great variety of works published on this topic[5, 12, 10, 6], there is no consensus about the best method for each case or all cases. The methods are usually evaluated using a different set of images and, due to these circumstances, it is impossible to establish a fair comparison among them. Besides, the error metric that has been consistently adopted in the literature is the difference in angle between the normal vectors of the estimated MSP and a ground-truth plane as defined by an expert. This metric is not adequate, because it does not take into account situations where the estimated MSP and the ground-truth plane are parallel and translated apart from each other. Even when their angular difference is small, they may touch each other very far from the center of the image, so inside the image the planes are very distant.

We have circumvented the aforementioned problems by developing a simple, fast, precise, and accurate method from the first group, and a new metric, called *average z-distance*, to measure the MSP estimation error as a function of the distances between corresponding pixels of each plane. The proposed approach was extensively evaluated with better results against two methods from the second group[9, 10] and another method from the first group[4], using a same dataset with 164 clinical images and the average z-distance metric. This work is described next.

2. THE METHOD

The novel algorithm for extracting the mid-sagittal plane (MSP) from a brain image first requires resampling to obtain a new image with isotropic voxels. The best MSP consists of the plane that maximizes a bilateral symmetry measure and this process relies on a multi-scale search.

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2.1. Quantifying Brain Symmetry

Our bilateral symmetry measure is based on edge features extracted from the image. It is essentially a score that indicates how similar are the left and right sides of an edge image with respect to a candidate cutting plane.

The edge detector used in this work is based on a 3D Sobel operator, which is fast and effective to enhance edges, followed by thresholding. The Sobel operator is also a band-pass frequency filter, which eliminates high-frequency noise, improving the robustness of the method. Figure 1 shows an example of the extracted edges for a given MR image of the head. We have observed that 5% of the brightest voxels in the enhanced image are enough to represent the edge features independent of the imaging protocol. Therefore, the edge detector results into a binary image o , where I_{ijk}^o indicates the value in $\{0, 1\}$ of a voxel at coordinate (i, j, k) .

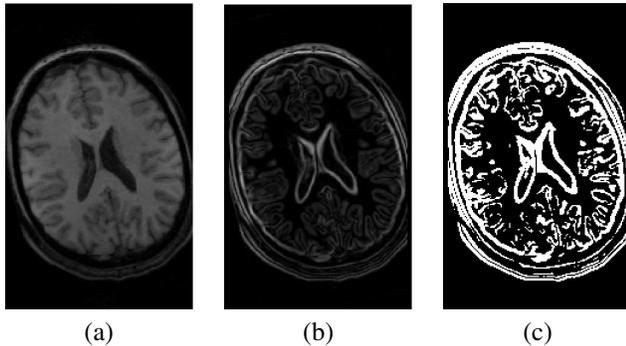


Fig. 1. Steps for edge detection. First, we apply the Sobel edge operator in the original image (a) to obtain image (b). Then we select the highest intensity voxels to obtain a binary image (c).

Given a candidate plane, we evaluate how symmetric the input neuroimage is with respect to this plane by measuring the correlation between the binary image o and its flipped copy f with respect to the candidate plane.

$$S = \frac{\sum_i^w \sum_j^h \sum_k^d I_{ijk}^o I_{ijk}^f}{\sqrt{(\sum_i^w \sum_j^h \sum_k^d I_{ijk}^o I_{ijk}^o)(\sum_i^w \sum_j^h \sum_k^d I_{ijk}^f I_{ijk}^f)}}$$

where w , h , d are width, height and depth of the 3D neuroimage, respectively; and I_{ijk}^f is the value in $\{0, 1\}$ of a voxel at coordinate (i, j, k) in the flipped image f . Note that this equation can be efficiently implemented by taking into account a list of non-zero (edge) voxels, i.e., coordinates (i, j, k) , in o and computing their flipped coordinates in f for any given plane. In this case, we measure S by simply counting the number of voxels in the flipped coordinate list which have value 1 in image o and dividing this number by the total number of voxels with $I_{ijk}^o = 1$. Note that we could have also applied the above equation in the enhanced image, avoiding thresholding, but the method has two advantages when used with binary images. Its implementation is much faster, as described above, and edge voxels are equally important independent of their value in the enhanced image, which makes the method more robust to outlier edges.

Figure 2 shows the symmetry scores computed for many planes in a pre-aligned image where the MSP is the central slice. The clear

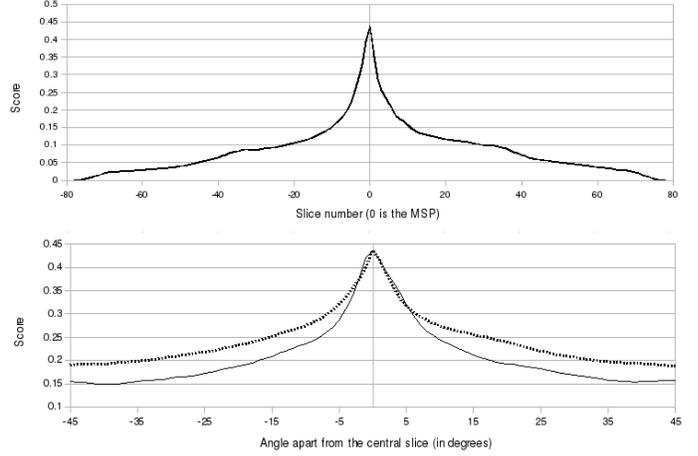


Fig. 2. The first chart shows the scores obtained for each of sagittal slices of a pre-aligned image. The second chart shows the scores for yaw (dashed line) and roll (continuous line) rotations apart from the midsagittal plane of a pre-aligned image. Both charts shows a clear peak in the MSP position.

peak in the MSP position shows that the measure we propose to quantify symmetry is potentially able to identify the MSP among other planes.

2.2. Multi-Scale Search of the MSP

The evaluation of all possible planes is not feasible in interactive time, due to the high number of possibilities. Therefore, we need a smart strategy to considerably reduce the search space and, at the same time, converge to the optimal solution.

The algorithm developed in this work is a 3-stage multi-scale search, where each stage refines the solution of the previous one. The first stage works on a 1/4-scaled image giving a rough approximation of the solution, the second stage provides a further refinement, working on a 1/2-scaled image, and the third works on the full-scale image, providing the final result. Because we are drastically reducing the number of voxels in the first stage (using about 1% of the edge voxels), it is possible to evaluate a high number of candidate planes in a short time and guarantee a good approximation of the MSP without getting stuck in any local maximum.

In this work, a plane is represented by a set of three points in the corners of the image. For sake of simplicity let us suppose that the input image is in sagittal orientation, and later we will explain how the method is extended for unknown orientations. The origin of our coordinate system is on the top-left corner of the image, being xy the plane of the sagittal slices, the axis z grows from first to the last slice, the axis x grows to the right, and the axis y grows to the bottom. So for an image in sagittal orientation, the candidate planes are defined by the following points: $P_1(0,0,z_1)$, $P_2(S_x - 1,0,z_2)$ and $P_3(S_x - 1,S_y - 1,z_3)$, where S_x and S_y are the sizes of the image along the x and y axes. Now, the parameters that define the possible candidates are z_1 , z_2 and z_3 . By varying these points it is possible to define any possible sagittal plane. This 3-point representation is interesting because it provides a unique representation for each plane. Other representations like a point and a vector allow that

different values of (point,vector) actually represent the same plane. In our representation, any plane is given by one and only one combination of parameters z_1, z_2 and z_3 . This property optimizes the search since it decreases the number of possibilities by not having redundant combination of parameters.

The first stage is a coarse search and works on a 1/4-scaled image, and in this stage we take into account all combinations of values for z_i in steps of 2 voxels, evaluating all planes defined by each combination. In other words, $z_1, z_2, z_3 \in [0 : S_z \mid z_1, z_2, z_3 \text{ is multiple of } 2]$.

The second step, starts the search on the result of the first stage. As the images in the first and second stages have different sizes, the result (points P_1, P_2 and P_3) from the previous stage has to be mapped to the new image size. Then, the second stage repeats the same procedure but now on a 1/2-scaled image. Because we already know that the plane found in the first stage is a good approximation, we can concentrate our search just around this plane. So, the second stage considers this mapped result as starting point and varies the parameters z_1, z_2, z_3 in steps of 1 voxel in a range of +/-4 voxels, which was the step size in the previous stage mapped to the new image size.

The final stage repeats exactly the same procedure of the previous stage on the full-scale image and considers steps of 0.5 voxels in a range of +/-4 voxels, so the expression would be $z_i \in [z_i - 4 : z_i + 4 \mid \text{multiple of } 0.5]$. We defined 0.5 as the maximum precision for the last stage because, for a typical MR image, a difference of 0.5 in one of the points that defines the plane leads to 0.23 degrees of rotation, which can be considered accurate enough for most purposes. If higher accuracy is desired, it can be achieved by lowering the step size of the last stage.

The method described up to now assumes a sagittal initial orientation, but our approach is actually able to work with images in any initial orientation (sagittal, axial or coronal) from one simple modification. When the initial orientation is unknown, the first stage is performed three times, one time for each orientation, and the orientation that gives the best symmetry score is considered to be the orientation of the image. Then, we permute the image axis in a way it becomes in sagittal orientation and then proceed in the other two stages, as previously described.

3. EVALUATION AND RESULTS

We have evaluated our method using three other approaches [9, 4, 10] as baselines. The first two methods are previous works of some authors of this paper. The method in [10] was carefully implemented according to the published article.

	Dataset	# of Images
1	MRI-T1 Normal	20
2	MRI-T1 Post Surgery	36
3	MRI-T1 Post Gad (Tumor)	55
4	MRI-T2 Normal	30
5	CT Normal	15
6	CT Stroke	8
	TOTAL	164

Table 1. The dataset used for evaluation

The algorithm proposed in this paper was implemented for both GNU/Linux and Windows platforms in C language and it is freely

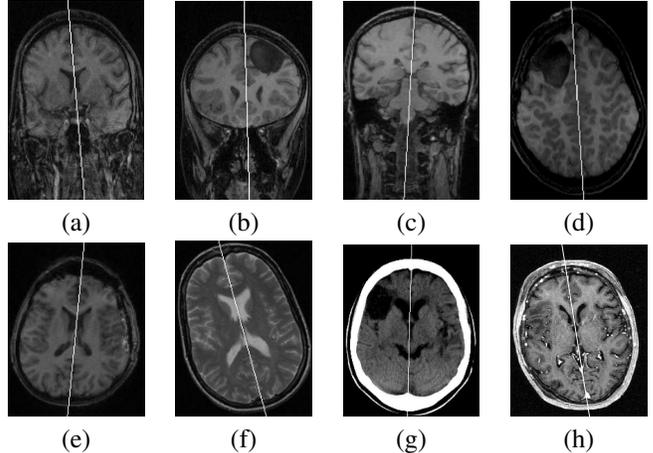


Fig. 3. Examples of sagittal planes extracted by our method. This figure shows our proposed method is able to extract MSP from both normal and pathological images.

available¹ for research purposes. It uses the Analyze 7.5 image format for both input and output images.

A total of 164 clinical images were available, including CT, MR-T2 and MR-T1 images with and without the injection of contrast agent. The dataset we used for this evaluation is summarized in Table 1. This dataset includes images from normal subjects, who usually presents higher symmetry, but it also includes pathological images that usually present accentuated asymmetry, due to the presence of tumors or parts removed by surgery. The images with tumors were obtained post-injection with the gadolinium contrast agent.

In order to compare all algorithms with the human performance, the ground truths for all images were generated through the manual marking of the MSP by an expert. We implemented a software specifically to mark ground truths of mid-sagittal planes. This software is called Mid Sagittal Plane Ground Truth Tool (MSPGTT) and is also freely available¹.

To measure the error between the ground truths and the results, the metric that has been used consistently in the literature is the angle between the normal vectors of these planes. As mentioned earlier, this metric is inadequate for this purpose because it does not provide a correct measurement of error. The most simple example of this problem is the case of parallel planes, which are translated apart from each other, but the angle between them is still zero. Another example is the case where the angle is small but the planes touch each other very far from the center of the image, so inside the image the planes become very distant. For this reason, we introduce a new metric for evaluating MSP results, called *average z-distance*. Supposing an image in sagittal orientation (not-aligned), the average z-distance is the average distance along the z axis for all points (x, y) inside the image between the ground-truth plane and resulting plane of the method. For each x and y, we compute the z coordinate for the ground truth plane and for the resulting plane, then compute the distance between them. This metric is also interesting because it gives a physical intuition of the displacement between the planes. For example, a measure of 1.2 means that the voxels in one plane are

¹<http://www.liv.ic.unicamp.br/~ruppert/msp>

Dataset	Our method			Volkau, 06 [10]			Teverovskiy, 06 [4]			Bergo, 06 [9]		
	Mean	σ	Median	Mean	σ	Median	Mean	σ	Median	Mean	σ	Median
1	1.27	0.59	1.07	1.84	1.14	1.45	1.46	0.81	1.22	1.46	0.93	1.36
2	1.68	0.82	1.44	3.22	5.06	2.16	2.19	1.33	1.87	1.9	1.18	1.71
3	1.46	0.70	1.47	4.64	1.97	4.55	1.64	0.89	1.40	-	-	-
4	1.54	0.80	1.31	2.89	1.82	2.37	1.42	0.7	1.21	-	-	-
5	2.93	2.02	2.08	6.16	11.29	3	3.54	1.93	3.41	-	-	-
6	2.83	1.89	2.84	6.39	10.32	2.46	3.45	3.26	2.34	-	-	-

Table 2. Accuracy (in voxels) of the evaluated methods using the average z-distance metric. The method [9] is only designed for MRI-T1 without contrast agent so it was not evaluated for the other modalities.

on average 1.2 voxels apart from the other plane.

We evaluated the methods for all images by computing their average z-distance with respect to each respective ground-truth plane. The results obtained for each image category of the dataset are shown in Table 2. These results indicate that the proposed method presents the highest accuracy and precision among the evaluated methods for all categories, except for MR-T2 images, where the results of the method in [4] were slightly better, but still very close. The method in [10] only performed close to the proposed method for MR-T1 images of normal subjects, but for the other categories its results were significantly worse. The method in [9] was designed specifically for MR-T1 images without contrast agent and it does not work with other image categories. As observed for all methods, the results for CT images were worse than for MR images. This occurred because the CT images available in our dataset present low image quality, with blur, noise and large slice thickness, which compromised the isotropic interpolation. But even under these conditions, the proposed method showed the best accuracy among all.

To evaluate the mean computational time, all MSP extraction algorithms were executed on the same machine (Intel Core2Quad Q8200 2.33Ghz 4GB RAM). The proposed method took 29.96 seconds on average. The method in [4] took 434.01 seconds, while the method in [9] computed the MSP in 49.79 seconds. The fastest approach was the method in [10], which took 6.69 seconds. However, it was the worst in accuracy and precision.

Therefore, considering a compromise among efficiency, accuracy, and precision, we may conclude that our algorithm outperformed the others. It is executed in interactive time and, although the method in [4] presents similar accuracy and precision to our approach, it is almost 20 times slower.

4. CONCLUSION

We have proposed a fast, accurate and precise method for the mid-sagittal plane (MSP) estimation in medical images of the head. Our method exploits symmetry maximization to locate the MSP and, although we did not tested it on all possible imaging protocols, it should be able to perform on any imaging protocol, as long as there is some degree of symmetry present in the image. Experiments using a large and heterogeneous dataset have shown that the proposed method provides the highest accuracy and precision among four evaluated algorithms, takes into account different image orientations, and yields fast computation in interactive time. The ground-truth labeling software and the average z-distance metric proposed in this work are also contributions that we expect to enable more

comparative works on this topic.

5. REFERENCES

- [1] F.P.G. Bergo, A.X. Falcão, C.L. Yasuda, and F. Cendes, "FCD segmentation using texture asymmetry of MR-T1 images of the brain," in *The Fifth IEEE Intl. Symp. on Biomedical Imaging: From Nano to Macro (ISBI)*, Paris, France, 2008, pp. 424–427.
- [2] Y. Liu, L. A. Teverovskiy, O. L. Lopez, H. Aizenstein, C. C. Meltzer, and J. T. Becker, "Discovery of biomarkers for alzheimer's disease prediction from structural MR images," in *2007 IEEE Intl. Symp. on Biomedical Imaging*, April 2007, pp. 1344–1347, IEEE.
- [3] L. Teverovskiy, J. Becker, O. Lopez, and Y. Liu, "Quantified brain asymmetry for age estimation of normal and Alzheimer's disease/mild cognitive impairment subjects," in *Proc. of the 5th Intl. Symp. on Biomedical Imaging: From Nano to Macro (ISBI)*, Paris, France, May 2008, pp. 1509 – 1512, IEEE.
- [4] L. Teverovskiy and Y. Liu, "Truly 3D midsagittal plane extraction for robust neuroimage registration," in *Proc. of 3rd IEEE Intl. Symp. on Biomedical Imaging*, April 2006, pp. 860–863, IEEE.
- [5] Y. Liu, R. T. Collins, and W. E. Rothfus, "Robust midsagittal plane extraction from normal and pathological 3D neuroradiology images," *IEEE Trans. on Medical Imaging*, vol. 20, no. 3, pp. 175–192, Mar 2001.
- [6] S. Prima, S. Ourselin, and N. Ayache, "Computation of the mid-sagittal plane in 3D brain images," *IEEE Trans. on Medical Imaging*, vol. 21, no. 2, pp. 122–138, Feb 2002.
- [7] A. V. Tuzikov, O. Colliot, and I. Bloch, "Evaluation of the symmetry plane in 3D MR brain images," *Pattern Recognition Letters*, vol. 24, no. 14, pp. 2219–2233, Oct 2003.
- [8] S. M. Smith and M. Jenkinson, "Accurate robust symmetry estimation," in *Proc MICCAI '99*, London, UK, 1999, pp. 308–317, Springer-Verlag.
- [9] F. P. G. Bergo, G. C. S. Ruppert, and A. X. Falcão, "Fast and robust mid-sagittal plane location in 3D MR images of the brain," in *Proc. of the International Conference on Bio-inspired Systems and Signal Processing*, Jan 2008.
- [10] I. Volkau, K. N. B. Prakash, A. Ananthasubramaniam, A. Aziz, and W. L. Nowinski, "Extraction of the midsagittal plane from morphological neuroimages using the Kullback-Leibler's measure," *Medical Image Analysis*, vol. 10, no. 6, pp. 863–874, Dec 2006.
- [11] R. Guillemaud, P. Marais, A. Zisserman, B. McDonald, T. J. Crow, and M. Brady, "A three dimensional mid sagittal plane for brain asymmetry measurement," *Schizophrenia Research*, vol. 18, no. 2–3, pp. 183–184, Feb 1996.
- [12] Q. Hu and W. L. Nowinski, "A rapid algorithm for robust and automatic extraction of the midsagittal plane of the human cerebrum from neuroimages based on local symmetry and outlier removal," *NeuroImage*, vol. 20, no. 4, pp. 2153–2165, Dec 2003.