A New Medical Image Analysis Approach Integrating Expert Systems and Deformable Models

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<u>Participants:</u>
1. Hamid Soltanian-Zadeh, PhD, Principal Investigator
2. Kost V Elisevich, PhD, Co-Investigator
3. Amir Ghanei, PhD Candidate
4. Mohammad Reza Siadat, PhD Candidate
5. Lucie Bower, BS, Software Specialist

1. Major activities of the project

1.1. Development of a knowledge-based system for localizing hippocampus in human brain MRI

Hippocampus is an important structure of the human brain limbic system. The variations in the volume and architecture of this structure have been related to certain neurological diseases such as schizophrenia and epilepsy. We have been developing a two-stage method for localizing hippocampus in human brain MRI automatically. The first stage utilizes image processing techniques such as histogram filtering and analysis to extract information from MRI. This stage generates binary images and locates lateral ventricles, third ventricle, and Sylvian fissure. To localize structures and find candidate landmarks around hippocampus, we use computer vision search algorithms and extract connected regions in the binary images. The second stage uses an expert system to analyze the information extracted in the first stage. This stage utilizes absolute and relative spatial rules and spatial symmetry rules to determine validity and consistency of the candidate landmarks found in the information extraction stage. Based on the results, it determines whether a slice contains hippocampus or does not contain it. For the slices with hippocampus, it determines multiple landmarks close to the hippocampus boundaries. Hippocampus landmarks found by the method define initial shape for a 3D deformable model to segment hippocampus.

1.2. Development of a 3D deformable surface model to segment hippocampus using the image data and the location information generated by the knowledge-based system

We have been developing a knowledge-based deformable surface for segmentation of medical images. This work has been done in the context of segmentation of hippocampus from brain MRI, due to its challenge and clinical importance. The model has a polyhedral discrete structure and is initialized automatically by analyzing brain MRI and finding a few landmarks on each slice using an expert system. The expert system decides on the presence of the hippocampus and its general location in each slice. The landmarks found are connected together by a triangulation method, to generate a closed initial surface. The surface deforms under defined internal and external force terms thereafter, to generate an accurate and reproducible boundary for the hippocampus. The anterior and posterior (AP) limits of the hippocampus is estimated by automatic analysis of the location of brain stem, and some of the features extracted in the initialization process. These data are combined together with a priori knowledge using Bayes method to estimate a probability density function (pdf) for the length of the structure in sagittal direction. The hippocampus AP limits are found by optimizing this pdf.

1.3. Construction of simulations and acquisition of actual patient data for evaluation and validation of the image analysis methods

In testing and evaluation of the algorithms, computer simulations are the only test objects in which the "truth" is known on a pixel-by-pixel basis. We use simulations as "gold standards" for testing and evaluating the software and algorithms developed in this project. We have been using the following two methods to generate simulations.

In the first method, we use regular and irregular shaped geometric objects (spheres, ellipsoids, cylinders, and cubes) that fit together to form a three-dimensional scene. The contrast used in the simulation is similar to the contrast between the white matter and the gray matter in typical human MRI brain studies. White noise with different powers is added to the simulation to gauge sensitivity of the results to the noise power. The noise power is varied around that estimated from human brain MRI's.

In the second method, we use the eigenimage method, developed in our previous research, to segment normal tissues (white matter, gray matter, CSF) from actual MRI brain images. The Neurosurgeon-Neuroanatomist Co-Investigator defines the boundaries of the hippocampi. We reconstruct the resulting objects into 3D simulations. In these simulations, objects are assigned gray levels based upon average gray levels obtained for the brain tissues in MR images. Regions representing partial volume averaging are included in the scene. For the partial volume regions, the fractional components are known on a pixel-by-pixel basis from the eigenimage method results. To generate Rician distributed noise in the simulations (similar to that of real MRI), we add Gaussian noise to the free induction decay (FID) signals and reconstruct images using Fourier transformation. Non-uniformity effects are added to the images. Also, by convolving the reconstructed images with the system's point spread function (PSF) for the protocols with PSF significantly different from a delta function, simulated images include the effects of MRI PSF.

We have been collecting actual brain studies of the epileptic patients so that we can evaluate our algorithms using these real data. These studies consist of sagittal and coronal (oblique) MRI (T1-, T2-, and PD-weighted images), the EEG analysis results, and the postsurgery outcomes of epileptic patients. The EEG analysis results and the clinical outcomes are considered as the "gold standards." The Neurosurgeon-Neuroanatomist Co-Investigator assesses all patients presenting with complex partial seizure disorders and refers them for the image analysis study with their approval. To avoid any bias, the patient studies used in developing the algorithms are not used in the testing phase. The MRI data are analyzed retrospectively to test, evaluate, and validate the image analysis methods and to perform clinical hypotheses testing. The imaging sequence utilized for epilepsy studies at Henry Ford Health System, Detroit, MI, consists of a sagittal localizer, two axial T2-weighted multiple spin echo images (TE/TR = 30,90/2500 ms), a coronal T1-weighted spin echo (TE/TR = 25/500 ms), and a coronal FLAIR image (TE/TI/TR= 119/2200/10002 ms). For the coronal images, contiguous 3 mm thick slices are obtained with a 256x256 matrix and a 25 cm FOV resulting in a voxel dimension of 0.78x0.78x3 mm. Imaging time is approximately 30 minutes.

2. Major findings

We have been using simulated and real MRI T1-weighted images to evaluate the methods. We have applied the knowledge-based method developed for hippocampus localization to 128 images (60 slices with the hippocampus and 68 slices without it) of six epileptic patients. The results for information extraction and information analysis steps are reported separately in the papers. Here, we summarize major results.

1. The proposed system correctly identified all of the slices without the hippocampus and correctly localized hippocampus in about 60% of the slices with the hippocampus. The moderate success rate for the slices with the hippocampus is a consequence of the high threshold value used to prevent false positives. Note that this success rate satisfies requirements of our application, since the hippocampus landmarks found by the method define a reasonable coarse model of the hippocampus that is used by the 3D deformable model to determine accurate boundaries of the hippocampus in all slices.

2. Most of the failures were caused by the shortcomings in creating the binary images. Thus, improving the approach for this part of the method is crucial in order to increase the success rate of the method.

3. Since the expert system uses several symmetry-based rules, if the image is asymmetric, the method may not work properly. Asymmetry may be generated when the slice direction during the imaging is oblique towards the sagittal direction. In this case, the correction is simple: reslice the 3D volume in the right coronal direction. Although rare for epileptic patients, asymmetry may also be produced by an abnormal tissue, e.g., a tumor. In this case, the expert system cannot use the symmetry-based rules and alternative rules are needed.

4. Using the initial points found by the methods developed, a 3D deformable model is expected to segment the hippocampi accurately.

3. Outreach activities

We have been actively presenting the research results at scientific meeting and publishing them in the conference proceedings and journals.

3.1. Presentations and abstracts

1. A. Ghanei, A. Ratkewics, F. Yin, H. Soltanian-Zadeh, "A 3D Deformable Model for Segmentation of Human Prostate from Ultrasonic Images." Presented at the World Congress on Medical Physics and Biomedical Engineering -- WC2000, Chicago, IL, July 2000.

2. D.J. Peck, D.O. Hearshen, H. Soltanian-Zadeh, Renee R. Lajiness-O'Neill, "Analysis of fMRI Using a Linear Filter." Presented at the World Congress on Medical Physics and Biomedical Engineering -- WC2000, Chicago, IL, July 2000.

3. M.A. Jacobs, S. Patel, H. Soltanian-Zadeh, P. Mitias, D.J. Peck, A. Ghanei, R. Hammoud, I. Duhaini, M. Chopp, "Unsupervised Segmentation of Clinical Stroke with Multiparameter MRI," Presented at and Published in the Book of Abstracts of the 8th ISMRM Meeting, Denver, CO, April 2000.

4. M.A. Jacobs, R.A. Knight, D.J. Peck, H. Soltanian-Zadeh, Z.G. Zheng, A.V. Goussev, R. Hammoud, I. Duhaini, M. Chopp, "Tissue Characterization of Multiparameter MRI with Histopathological Validation in Experimental Cerebral Ischemia in Rat," Presented at and Published in the Book of Abstracts of the 8th ISMRM Meeting, Denver, CO, April 2000.

5. M.A. Jacobs, Z.G. Zheng, R.A. Knight, H. Soltanian-Zadeh, P.D. Mitsias, S. Patel, Q. Jaing, A.V. Goussev, M. Chopp, "Multiparameter MRI Tissue Staging in Experimental Cerebral Ischemia in Rat," 25th International Stroke Meeting, New Orleans, LA, Feb. 2000.

3.2. Proceedings articles

1. H. Soltanian-Zadeh, M. Kharrat, D. J. Peck: "Polynomial transformation for MRI feature extraction." Presented at and Published in the Proceedings of SPIE Medical Imaging 2001: Image Processing Conference, San Diego, CA, Feb. 17-22, 2001.

2. A. Shahrokni, R. A. Zoroofi, H. Soltanian-Zadeh: "Fast skeletonization algorithm for 3D elongated objects." Presented at and Published in the Proceedings of SPIE Medical Imaging 2001: Image Processing Conference, San Diego, CA, Feb. 17-22, 2001.

3. H. Soltanian-Zadeh, A. Shahrokni, R. A. Zoroofi: "Voxel-coding method for quantification of vascular structure from 3D images." Presented at and Published in the Proceedings of SPIE Medical Imaging 2001: Physiology and Function from Multidimensional Images Conference, San Diego, CA, Feb. 17-22, 2001.

4. A. Ghanei, H. Soltanian-Zadeh, K. Elisevich, J. A. Fessler: "Knowledge-based deformable surface model with application to segmentation of brain structures in MRI." Presented at and Published in the Proceedings of SPIE Medical Imaging 2001: Image Processing Conference, San Diego, CA, Feb. 17-22, 2001.

5. H. Soltanian-Zadeh, R. Hammoud, M. A. Jacobs, S. C. Patel, P. D. Mitsias, R. Knight, Z. G. Zheng, M. Lu, M. Pasnoor, M. Chopp: "Tissue characterization in cerebral ischemia using multiparameter MRI." Presented at and Published in the Proceedings of SPIE Medical Imaging 2001: Physiology and Function from Multidimensional Images Conference, San Diego, CA, Feb. 17-22, 2001.

6. M.R. Siadat, H. Soltanian-Zadeh: "Partial volume estimation using continuous representations." Presented at and Published in the Proceedings of SPIE Medical Imaging 2001: Image Processing Conference, San Diego, CA, Feb. 17-22, 2001 (Received Honorable Mention Award).

7. H. Soltanian-Zadeh, S. Pourabdollah-Nezhad, F. Rafiee Rad: "Shape-based and texture-based feature extraction for classification of microcalcifications in mammograms." Presented at and Published in the Proceedings of SPIE Medical Imaging 2001: Image Processing Conference, San Diego, CA, Feb. 17-22, 2001.

8. H. Soltanian-Zadeh, D.J. Peck, and D.O. Hearshen: "Optimal linear filter for fMRI analysis." Presented at and Published in the Proceedings of SPIE Medical Imaging 2000: Image Processing Conference, San Diego, CA, Feb. 2000.

9. H. Soltanian-Zadeh, S. Pourabdollah-Nezhad, and F. Rafiee-Rad: "Texture feature extraction methods for microcalcification classification in mammograms." Presented at and Published in the Proceedings of SPIE Medical Imaging 2000: Imag Processing Conference, San Diego,CA, Feb. 2000 (Received Honorable Mention Award).

10. H. Soltanian-Zadeh, L. Scarpace, and D.J. Peck: "Feature space analysis: effects of MRI protocols." Presented at and Published in the Proceedings of SPIE Medical Imaging 2000: Image Processing Conference, San Diego, CA, Feb. 2000 (Received Honorable Mention Award).

3.3. Journal publications

1. A. Ghanei, H. Soltanian-Zadeh, M. Jacobs, S. Patel, "Boundary-based Warping of Brain MR Images," Boundary-based Warping of Brain MR Images, vol. 12, no. 3, pp. 417-429, Sept. 2000.

2. M.R. Siadat and H. Soltanian-Zadeh, "Localization of Hippocampus in Human Brain MRI Using an Expert System." Journal of Faculty of Enineering at the University of Tehran, vol. 34, no. 1, June 2000.

4. Contributions of the project

In recent years, deformable models have been proposed for many scientific applications. In the field of image processing and medical imaging, they have been proposed for segmentation, motion tracking, tracking of deformations, volumetry, image warping, brain mapping, modeling of the human body or brain structures, and surgery simulation. In computer science, they have been proposed for 3D visualization (facial modeling), computer aided design (CAD), animation, pattern recognition (recognition of hand written characters - OCR), machine vision, augmented reality, tracking of objects or scenes (e.g., hand tracking), geometric design, visual analysis, shape recovery (from database of shapes), and parameterization of surfaces and contours. In industry, they have been proposed for motion tracking, pattern recognition (e.g., vehicle's part recognition), simulation (e.g., behavior of liquid in different media, solid modeling), physical modeling, and CAD.

All deformable models start from an initial shape (state) and evolve until they come to a final shape (rest state). Initially, researchers left definition of the initial shape to the user, resulting in low productivity and low reproducibility of the results. In recent years, certain researchers have addressed the problem of initialization in deformable models. Some of these researchers have used a fixed template (or atlas) for defining the initial shape. This method is clearly insufficient for objects having large deformations. Others have used an initial (over) segmentation of the object, generated by Markov random field based segmentation or other low level image processing methods. These methods need careful setting of the segmentation parameters and are not suitable for objects with no boundaries or faint boundaries in certain parts of the image, e.g., liver, hippocampus, and other brain regions in medical images.

When the object of interest is a substructure of a main object, some researchers have proposed the initialization by warping an atlas to the main object. For example, when a structure inside the brain is desired, a brain atlas is registered and warped onto the subject's brain images. Then the corresponding internal structure in the atlas defines the initial shape for the model. When the internal object is relatively small, this method will not generate good results, due to its sensitivity to the imperfections involved with the registration and warping steps.

We are developing image processing methods along with an expert system to define the initial shape, using a priori knowledge about the problem in hand. The expert system analyzes the information extracted from the images to define a reliable initial shape, thereby overcoming difficulties associated with the previous methods. We develop the methods in the context of an important biomedical application (segmentation and characterization of hippocampus from brain MRI). Compared to other intelligent analysis methods, e.g., Bayesian networks, expert systems have the advantage of being able to benefit from the a priori knowledge in the form of logical rules without a need for numerous examples or probability density functions, which are hard to estimate. They can be designed to work based on the global image properties and generate results that are insensitive to the size and details of the desired object and its surrounding environment.

The 3D deformable surface model being developed in this project consists of triangle patches. Compared to other 3D models, this structure is more appropriate for the type of application considered in this project. It is also well suited for industrial applications that use finite element methods. Algebric surfaces (e.g., super-quadrics and splines) generate a concise representation, but they have limited expressiveness and flexibility. Spherical harmonics such as Fourier series and wavelets for representation of real physical structures in medicine and industry need lots of terms, which increase the calculations. Discrete particle systems and cloud of points do not generate enough integrity for the model, and by reducing their resolutions, their behavior can suddenly degrade.