SIGNAL PROCESSING IN MEDICAL IMAGING AND IMAGE-GUIDED INTERVENTION

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ABSTRACT

This is an introduction to a special session of ICASSP devoted to signal processing techniques in medical imaging and image analysis that consists of this introduction and 5 research presentations, each addressing one aspect of the medical imaging field in which signal processing plays an irreplaceable role. The topics cover a broad spectrum of medical imaging problems from image acquisition to image analysis to population-based anatomical modeling. The focus is on technical aspects of the problem and proposed/developed solutions with sufficient emphasis given to the introducing the biomedical importance of the problem as well as its signal processing relevance.

***Index Terms*—** Medical imaging, signal processing.

1. INTRODUCTION

Medical image acquisition has revolutionized many routine medical diagnostic and treatment procedures. A number of imaging modalities, starting with more than 100 years old X-rays, and including magnetic resonance imaging (MRI), computed tomography (CT), single-photon emission tomography (SPECT), positron emission tomography (PET), ultrasound, optical coherence tomography (OCT), and others have become common in hospitals and physician offices around the world. Development and existence of each of these modalities is heavily dependent on advances achieved in the general field of signal processing that lead to our ability to image in vivo biological structures in 2-D, 3-D, 4-D and most recently 5-D.

2. IMAGE ACQUISITION

Medical imaging provides image information from a variety of scanners. X-ray projection images (e.g., chest X-ray) serve as an example of a common 2-D imaging modality. While 2-D imaging has been the workhorse of the medical imaging technology for most of the 20^{th} century, 3-D modalities like X-ray CT, MRI, SPECT, or PET have become commonly used in the last decade of the past century. These scanners (especially CT and MR) are more and more frequently used in the 4-D mode depicting motion together with 3-D structure and/or morphology – MR imaging of a beating heart or CT imaging of breathing lungs may serve as examples. In this context, 5-D imaging represents, e.g., longitudinal imaging of a beating heart or a cancerous tumor inside of a breathing lung over a period of several days/weeks/months to depict temporal changes in morphology and/or function.

Traditionally, medical imaging relied on 2-dimensional approaches to image formation. Starting with the first X-ray image in 1895, X-rays have become an invaluable means of imaging the internals of the human body. The X-ray technology became tomographic and later 3-dimensional when Radon transform facilitated image reconstruction from projections caused by a rotating X-ray beam. A number of multi-beam scenarios currently exists including fan-beam imaging and subsequent reconstruction. By combining multiple X-ray sources and multiple X-ray detectors, with a rotational speed of 0.28 sec and axial scanning speed of more than 40 cm/sec, the entire chest region can be imaged in about 0.5 sec and the entire human body head to toe in about 5 seconds.

Magnetic resonance imaging represents another inherently 3-D/4-D imaging modality. In MRI, high-strength magnetic field is used to align the magnetization of hydrogen atoms in water which forms most of the human body. Magnetization alignment may be altered by radio frequency fields, forming a rotating magnetic field of the hydrogen nuclei. This field is detected by the MR scanner. With a complex signal manipulation, 2-D, 3-D, or 4-D images can be formed.

A number of other imaging modalities exist – ultrasound allows 2-D, 3-D and most recently 4-D (also called real-time 3-D) imaging. Optical coherence tomography (OCT) is emerging as a very-high resolution imaging modality – due to its high frequency of the utilized laser light, the depth of penetration is relatively low. Despite this fact, OCT has found tremendous use in non-invasive 3-D imaging of the human retina and in coronary plaque cap imaging.

Any of the mentioned modalities relies very heavily on advanced and complex signal processing pipelines to perfect the acquired image signal and thus provide the highest quality and highest resolution images available. Achieving good image quality while subjecting the patients to minimal doses of ionizing radiation, inherent to some imaging techniques, is an important challenge for the signal processing community.

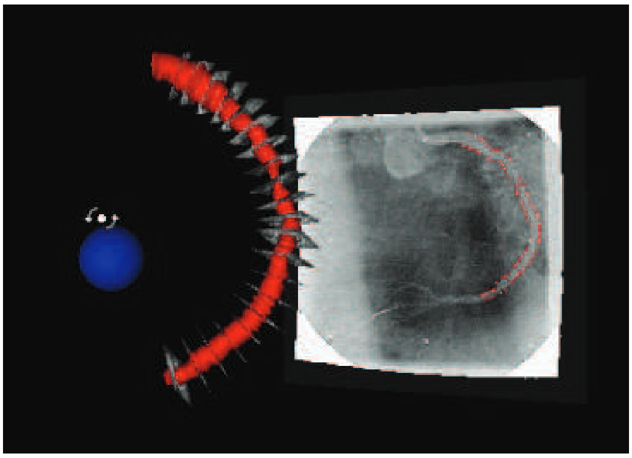
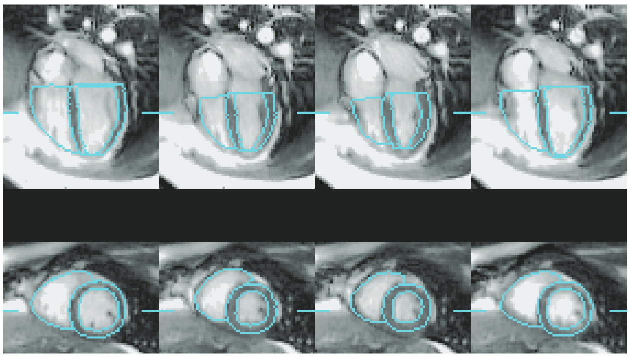
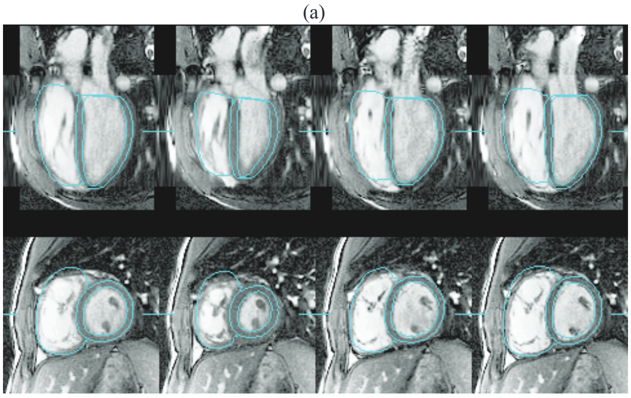


Fig. 1. 3-D geometrically correct reconstruction of human coronary artery imaged in vivo using biplane X-ray angiography and intravascular ultrasound (IVUS). Note the X-ray projection image with coronary boundaries segmented and a subset of IVUS images fused with the 3-D reconstructed coronary artery.

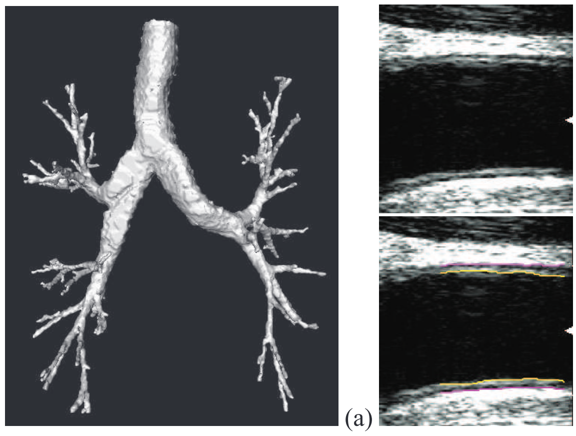


(a)



(b)

Fig. 2. 4-D MR segmentation of a normal heart (a) and a tetralogy of Fallot heart (b) at several cardiac phases. The line segments mark the locations of slices.



(a) (b)

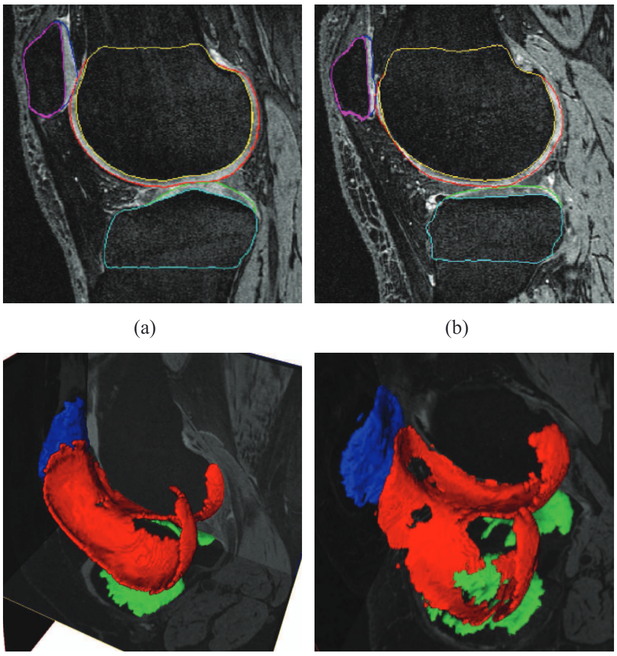
Fig. 3. (a) Intrathoracic airway tree segmentation from multi-detector X-ray CT. (b) Ultrasound image of a human carotid artery with intima-media thickness automatically determined.

3. IMAGE ANALYSIS

Despite the fact that image acquisition and subsequent visual assessment of the acquired images still represent the current standard of care even in the most developed countries, quantitative image analysis is slowly paving the way to more general acceptance. Motivated by the fact that humans are not very good in visual estimation of dimensions, especially in 3-D or higher dimensional spaces, that their estimates are highly irreproducible, and that manual tracing of structures of interest is tedious and time consuming (and still not reproducible), highly automated image analysis approaches have been increasingly sought and accepted in research applications. The clinical applications now closely follow with a number of clinically utilized quantitative analysis methods.

Quantitative analysis of coronary arterial stenoses was among the first routinely clinically accepted approaches to medical image analysis (Fig. 1) [1,2]. Numerous quantitative image analysis approaches exist in cardiologic applications, including quantitative analysis of coronary plaque from intravascular ultrasound [3], 3-D and 4-D analysis of morphology and function of the cardiac ventricles from ultrasound, CT, or MR images (Fig. 2) [4,5], and/or 4-D analysis of aortic morphology and function from MR images. Quantitative image analysis of ultrasound-imaged carotid arteries has been shown to provide early detection of systemic cardiovascular disease, and can serve as an independent predictor of heart attack and stroke (Fig. 3).

Many other application areas exists, including comprehensive systems for pulmonary image analysis from multi-detector CT images (Fig. 3), methods and approaches for brain image analysis (with substantial effort devoted to human brain anatomical analysis and functional mapping), orthopedic image analysis (e.g., quantitative analysis of articular cartilage in the knee joint – Fig. 4) [6], and a whole spectrum



(a) (b) (c) (d)

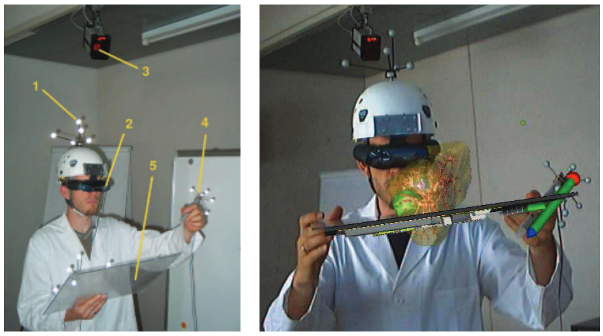
Fig. 4. 3-D segmentation of knee cartilages. Images from a knee minimally affected by osteoarthritis shown on the left. Severe cartilage degeneration shown on the right. Note the cartilage thinning and "holes" in panels (b,d).

of ophthalmic image analysis approaches now routinely used for population screening for diabetic retinopathy and other eye as well as systemic diseases [7].

The methods leading to successful, robust, accurate and reproducible quantitative analysis of multi-dimensional medical image data are becoming exceedingly complex, with a number of texts providing comprehensive treatment of the topic and the many existing linkages with signal processing methods and approaches [8, 9].

4. IMAGE-GUIDED INTERVENTION

Once image data are analyzed, their 3-D and/or virtual / augmented reality visualization can contribute to their usage for image-guided surgical interventions. A system for surgical treatment of liver cancer based on virtual liver resection developed by Beichel *et al.* may serve as an example [10, 11]. Surgical resection of cancerous tissue has become an established treatment for various types of liver tumors and is the method of choice for malignant liver tumors. Usually, resection is done on the basis of the eight autonomous liver segments in order to avoid devascularized liver tissue. Planning of surgical resections based on tomographic imaging modalities like CT and SPECT is a complex task, involving the identification of structures of interest (liver, vasculature, liver segments and tumors), followed by an assessment of the three-dimensional relationships between these objects, as well as the regional distribution of hepatic function. A Virtual Liver Surgery Planning System (VLSPS) was developed that consists of image analysis and image visualization parts. In the case of liver resection, the image analysis identifies the liver, liver tumors, and defines liver segments. Interactive visualization facilitates the virtual liver resection planning. The achievable improvements associated with the use of VLSPS include objective and reproducible results regarding segmentation and volume measurements, as well as exact identification of the involved liver segments. Figs. 5 – 7 demonstrate the functionality of the developed approach.

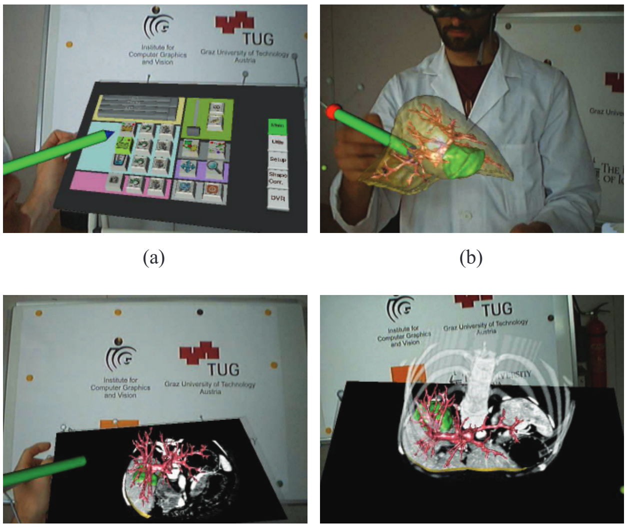


(a) (b)

Fig. 5. Augmented Reality Virtual Liver Surgery Planning System. (a) System components: (1) Tracking target mounted on top of the HMD, (2) Stereoscopic HMD for 3D viewing of virtual objects, (3) Infrared tracking camera for determining the position and orientation of the user and 3D input devices, (4) Tracked pencil (*PEN*), (5) Personal Interaction Panel (*PIP*). (b) Augmented Reality VLSPS in action.

5. CONCLUSION – THIS SPECIAL SESSION

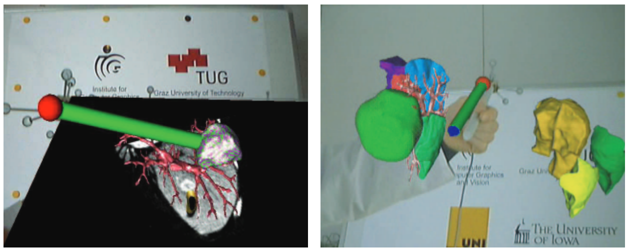
To allow cross-fertilization of ideas between medical imaging scholars and the broad signal processing community, this paper serves as an introduction to a special session that briefly overviews the state-of-the-art of medical imaging in the context of signal processing contributions. The focus is given to the entire chain of typical operation steps from image acquisition, reconstruction, processing, analysis, to visualization, as well as image guided therapies and interventions. Specifically, 3-D, 4-D, and 5-D imaging modalities are overviewed, and methods for quantitative analysis briefly discussed. The special session includes presentations devoted to *Efficient Image Reconstruction Under Sparsity Constraints with Application to MRI and Bioluminescence Tomography, The Meaning of Interior Tomography, Towards Integrated Analysis of Longitudinal Whole-Body Small Animal Imaging Studies, Time-Varying Lung Ventilation Analysis of 4D CT Using Image*



(a) (b)

(c) (d)

Fig. 6. Exploration of liver data sets within the augmented reality environment. (a) 3D controls on the *PIP* allow for application control and setting of rendering parameters. (b) Observation of the organ from different viewpoints and distances by walking around or directly moving the object. (c) The back-side of the *PIP* shows original CT data. (d) Direct volume rendering provides true 3D context information.



(a) (b)

Fig. 7. Resection planning and volume measurements. (a) Target selection using the *PEN*. (b) Resection Planning. Interactive removal of liver segments intersecting the tumor extended by a planning surgeon-specified safety margin.

Registration, and *Modeling Anatomical Heterogeneity in Populations*. The selection of topics serves two purposes – presentation of the standard chain of image acquisition and processing steps leading to clinical utility of medical imaging techniques, and providing direct linkages between the needs of the medical imaging community and the available expertise of the signal processing community. Signal processing is an enabling theory and technology behind the majority of medical image acquisitions, reconstruction, analysis, and visualization. With an increasingly omni-present barrage of quantitative medical imaging, analysis, and visualization and the growing demand for image guided interventional techniques, advanced signal processing is an integral part of almost any step in medical imaging research and clinical practice. Attracting the best signal processing researchers to become actively involved in this rapidly developing area is of utmost importance to the continuing progress.

6. REFERENCES

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