PROGRESS IN HIGH PERFORMANCE MEDICAL IMAGING

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ABSTRACT

Medical imaging has made great technological breakthroughs in multimodal acquisition, visualization, and analysis with many complementary image modalities to non-invasively capture human anatomy, physiology and pathology. New functional imaging techniques help elucidate the dynamics of human health and disease at much higher throughput, enabled by growth in affordable computing power, memory capacity, processor speed, and communication bandwidth. Recently, exceedingly powerful computer hardware and optimized image processing software may, for the first time, allow high volume image data processing and manipulation (like multimodal registration) to become clinically feasible on a routine basis in real-time. In reviewing recent medical imaging advances, we discuss some major open issues and directions.

1. INTRODUCTION

Advances in multimodal medical imaging contribute novel approaches to analysis and visualization for diagnosis and treatment, and allows much more detailed, personalized follow-up of patients in monitoring disease progression and response to treatment. An important long-term goal is the integration of structural and functional information to support therapeutic planning and practice. However, many open scientific issues in image registration, segmentation and interpretation/labeling remain open. The underlying computer representations in relation to mathematical modeling, visual (2-D and 3-D) rendering and mapping to atlases, ontologies, and the literature present formidable research challenges in designing systems to integrate large suites of multi-modal images under various assumptions about intra- and inter-patient variability. Technological innovation will be required for new acquisition modalities, fast pre-processing, and improved algorithms for automating analysis with the large datasets of heterogeneous information. Complexity of medical imaging is largely determined by trade-offs between robustness, automation, and speed requirements. For surgical procedures, for instance, imaging methods must be fast, yet simple, but techniques which satisfy speed requirements are often not sufficiently robust, requiring time-consuming user interaction. So, in order to achieve sufficient levels of robustness and automation, more complex mathematical methods are usually employed, and methods are often combined: registration, segmentation, and modeling are complementary and often used to support each other. High performance computing enables many robust and automatic medical imaging methods to be performed fast relying on efficient algorithms for volume rendering. In turn, efficient registration and classification algorithms combine to support segmentation and measurements between images before, during, and after treatment, against reference atlases. Major advances come when methods are parallelizable on high power multi-processor machines or over computing clusters and grids to solve very large systems of equations ($>10^5$). These analysis methods, in combination with novel modalities and acquisition technologies are systematically opening new opportunities for research and healthcare.

2. ADVANCES IN MEDICAL IMAGING

2.1 Image acquisition, communications and visualization

Three-dimensional and four-dimensional (time series) medical-imaging modalities such as computed tomography (CT), magnetic resonance imaging (MRI), ultrasound, fMRI, PET and SPCT and improved computer reconstruction, rendering and registration of multimodal and multidimensional medical and histological volume image data, are taking both structural and functional imaging beyond specialized research into very broadly applicable clinical investigations. Wider adoption of digital image acquisition enables advanced automatic or semi-automatic image processing and analysis techniques in areas as diverse as digital fundus imaging, digital colonoscopy [3][27] and digital microscopy [12][33]. However, as the acquisition of massive data from the new modalities increases, so does the need for more efficient ways of filtering the data to those subsets which are clinically significant, and this still relies much too strongly on expert human interaction due to the complexities of contextual factors in automating detection, registration, segmentation and labeling of what is diagnostically significant. Much still needs to be done to develop a better way of dealing with this critical issue. Digital picture archiving and communications systems (PACS) are increasingly sophisticated in functionality and performance, becoming ubiquitous, and increasing the effectiveness of medical practice. Research on medical image indexing/retrieval [23][29] combines high-level semantic information with low-level visual cues to achieve better accuracy and speed. The development of very rapid rendering and visualization graphics processors combined with advances in simulation and graphics models is leading to improved, real-time visualization capabilities for a wide variety of multimodal imaging methods, aiding considerably in their integration [22][30][34].

2.2 Multimodal registration

Automatic registration is essential for many clinical applications [7][9][13][15][17][21][49], with methods shifting significantly from surface-based approaches [14] to volume or voxel based approaches [31][7] in the past decade as a result of rapid improvements in computing power and main memory capacity. Yet, performance reliability and cost issues still largely limit these techniques to a relatively small number of large healthcare centers and medical research labs despite efforts in adapting them for routine clinical practice.

Some of the key challenges for research in the area of medical image registration involve: a) improving registration accuracy and efficiency, b) developing new registration methods with optimized algorithms for handling image data of various modalities and c) applicability to a wider range of anatomical structures as well as functional processes. However, most existing methods, though mathematically sound, often fail to achieve high accuracy and speed when dealing with data of different physical and morphological characteristics where original assumptions no longer hold. In [9] a viable approach is proposed for faster registration where data-specific characteristics are taken into account to reduce sample space, and thus computation load without sacrificing accuracy. Another major alternative for accelerating registration is to explore strategies for more efficient and rapidly converging computations. A good example of this class of techniques is the multi-resolution hill-climbing algorithm [26] where mutual information is used for registered MR-CT and MR-PET images of the human brain. In [24] an adaptive force technique is used to increase velocities and displacement in reaching stability in their fluid model for registration. Beyond algorithmic improvements, increasing attention has been given to hardware architecture-based parallelization and optimization because of emerging high performance architectures, such as cluster and grid computing, as well as advanced graphical processing units (GPU) and high power multi-core computers. In [31] a distributed computation framework is developed that would allow parallelization of registration metrics and medical image analysis algorithms for segmentation and visualization, while maximizing performance and portability. In [4] a parallel implementation of multimodal registration is reported for image guided neurosurgery using distributed and grid computing, where the registration time compared to traditional methods has been improved dramatically, to near real-time. One of the practical issues with cluster-based or grid computing architectures is availability and cost, since even for mid-size clinics financial limitations can be a major problem. The recent emergence of low cost, high power multi-core processor systems [1][11] have opened up an alternative venue for developing cost-effective high performance medical imaging techniques. In [18], a real time implementation of mutual information based registration is reported which uses a cell processor. They developed a new data partition scheme and parallel algorithm to speed up the process to a level of exceedingly high performance for a specific registration application.

2.3 Segmentation, classification and modeling: a major challenge for methodological integration

The problem of automating even parts of the segmentation of large multimodal medical image datasets is one of the most persistent and difficult problems in increasing the productivity or throughput of radiological and other image interpretation tasks [47]. The critical issue is the dependence of segmentation on the underlying model of the image, its clinical context of acquisition, and whether it is for generalized screening vs. detection of a clinically suspected problem. This is a general diagnostic problem for which neither computer vision nor AI have made sufficient progress in the past [35]. Nevertheless, hopeful possibilities include development and application of ontological frameworks [36] [37], models of deformable morphological characteristics of tissue and anatomical structures as well as image texture and other features [38][39], and diffusion tensor methods [40]. Most of the fundamental issues revolve around the inverse problem being tackled, and how it can be integrated within a practical framework of imaging reconstruction for a specific patient, or populations of patients to assess efficacy of imaging procedures [41]. While there have been many advances in methods of segmentation over the past few years, most still are demonstrated retrospectively on limited examples of specific imaging modalities for particular problems, suggesting that generalization of segmentation by automated methods remains elusive. Practical high throughput systems for multimodal imaging still rely in critical ways on interactive intervention of clinical experts to reduce bottlenecks and resolve ambiguities as steps towards automation [42].

2.4 Atlas-based medical imaging: a promising frontier

Atlas-based approaches [28] are gradually emerging as one of most promising frontiers in high performance medical imaging. These involve techniques that can facilitate almost every aspect of medical imaging from pre-processing, to analysis and interpretation, in many clinical applications [5][8][16][19]. One of the fundamental technical limitations with most existing medical imaging systems is the inability to explicitly and systematically represent or encode anatomical models of image objects in ways that provide the most structural and spatial constraints. Such contextual knowledge can play a vital role in minimizing the solution space, thus enabling more effective and efficient image problem solving. For instance, many pathological regions may share the same image intensity properties with normal regions or structures. Registration of patient image sets to atlases or models will help differentiate true positives from false positives [10]. In many types of image segmentation tasks, superimposing an anatomical model or atlas over an image can help the system to directly focus on the parts of the image corresponding to the target structures. While significant overhead can be incurred in mapping or registration with an atlas, real-time registration with much improved methods, algorithms and cost-effective computing hardware can be expected to overcome this limitation in the near future. In real world clinical applications, atlas mapping can be carried out as a part of preprocessing, independent of different kinds of application processes such as segmentation and analysis, surgery planning, labeling and indexing, etc. The potential of anatomical atlas imaging goes far beyond the current scope of clinical practice, research and education. One such opportunity of significant value is truly automated annotation. Although atlas-assisted medical imaging has become a very active area of research, it is still largely limited to a relatively small number of major centers mainly due to limitations in accuracy and efficiency of current mapping or registration methods in dealing with very large volumes of image and the variations and often inconsistent image properties of anatomical structures across different image modalities. Shortcomings in standardization in volumetric, geometric, and statistical aspects of atlas representation are also obstacles to their general adoption in broader communities of clinical practice.

3. HPC AND MULTIMODAL IMAGING: OPPORTUNITIES AND CHALLENGES

The major advances in multimodal imaging are targeted to improving diagnostic accuracy and precision and to provide guidance in a wide variety of diagnostic and treatment problems

[43][44] and advanced fluid-structure interactions [45]. With aging of populations there is increasing interest in developing techniques for early identification of neurological pathologies, such as related to Parkinsonism and Alzheimer's disease [48]. This involves major functional imaging correlative studies of the human brain under different conditions of perceptual and cognitive stimuli. In the US, the NIH has made a major effort in funding consortia for providing not only the imaging but also its informatics infrastructure (BIRNs) [46]. This then helps tie into novel studies of function and the effects of a wide range of treatments.

Major opportunities in healthcare for high performance multimodal imaging can be summarized as follows:

1) real-time image-guided diagnosis and treatment beyond the major academic medical centers;
2) scaling up multimodal integration of imaging at point of care;
3) integration of imaging with genomic/proteomic datasets for characterizing human phenotypes;
4) widespread use of medical imaging for health education from patients to healthcare providers.

Major technical challenges include:

1) innovative advanced imaging devices that can reveal structure and function at multi-scale resolutions at the anatomical, tissue, and even molecular levels across species;
2) inter-patient and intra-patient registration of massive multi-modal volumetric data;
3) generalizing segmentation methods beyond the problem- and modality-specific; more general or automated composition process using data-specific processing components;
4) consistent integration of shape, textural and color properties of images for standardizing descriptions – link to DICOM and other standards;
5) labeling/annotation of images based on ontologies and models – indexing of large imaging sets in real time;
6) re-use of massive image data sets for population-based studies, comparative analyses with new image data to assist better diagnosis, and clinical research..

4. CONCLUSION

Biomedical imaging opens up one of the greatest opportunities for medicine in the 21st Century: making it possible to computationally leverage and amplify the most powerful of human senses, vision, to help improve our understanding of human biology, and with it, human healthcare. It is already predicted that the lifespan of people will be extended considerably based on our better understanding of health and disease. Discovery of associations between genetic and environmental factors and pathological conditions have traditionally relied on correlation with biopsy or autopsy results. Medical imaging provides non-invasive methods for investigating human health from birth to death in response to environmental insults. High technology and high performance imaging, then, is at the center of making the critical associations visible and intelligible to not only researchers and clinical specialists, but to the very patients who rely on both technology and healthcare providers to help humankind lead increasingly healthier, longer lives.

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