Medical Image Processing: From Formation to Interpretation

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Technological advancements achieved in medical imaging over the last century created unprecedented opportunities for noninvasive diagnostic and established medical imaging as an integral part of healthcare systems today. One of the major areas of innovation representing these advancements is the interdisciplinary field of medical image processing.

This field of rapid development deals with a broad number of processes ranging from raw data acquisition to digital image communication that underpin the complete data flow in modern medical imaging systems. Nowadays, these systems offer increasingly higher resolutions in spatial and intensity dimensions, as well as faster acquisition times resulting in an extensive amount of high quality raw image data that must be properly processed and interpreted to attain accurate diagnostic results.

This article focuses on the key areas of medical image processing, considers the context of specific imaging modalities, and discusses the key challenges and trends in this field.

Core Areas of Medical Image Processing

There are numerous concepts and approaches for structuring the field of medical image processing that focus on different aspects of its core areas illustrated in Figure 1. These areas shape three major processes underlying this field—image formation, image computing, and image management.

The process of image formation is comprised of data acquisition and image reconstruction steps, providing a solution to a mathematical inverse problem. The purpose of image computing is to improve interpretability of the reconstructed image and extract clinically relevant information from it. Finally, image management deals with compression, archiving, retrieval, and communication of the acquired images and derived information.

Data Acquisition	Detection, Conversion, Preconditioning, and Digitization of Acquired Raw Data	Image Formation
Reconstruction	Analytical and Iterative Algorithms Providing a Solution to Inverse Problems	
Enhancement	Spatial and Frequency Domain Techniques for Improvement of Image Interpretability	Image Computing
Analysis	Segmentation, Registration, and Quantification	
Visualization	Image Data Rendering to Visually Represent Anatomical and Physiological Information	
Management	Storage, Retrieval, and Communication of Imaging Data	

Figure 1. Structural classification of the topic categories in medical image processing.

Image Formation

Data Acquisition

The first integral step in the image formation is an acquisition of raw imaging data. It contains the original information about captured physical quantities describing internal aspects of the body. This information becomes the primary subject for all subsequent steps of image processing.

Different types of imaging modalities may utilize different physical principles and thus involve detection of different physical quantities. For example, in digital radiography (DR) or computed tomography (CT), it is the energy of incident photons; in positron emission tomography (PET), it is the photons energy and their detection time; in magnetic resonance imaging (MRI), it is the parameters of a radio-frequency signal emitted by the excited atoms; and in ultrasonography, it is the parameters of the acoustic echoes.

However, regardless of the type of imaging modality, the data acquisition process can be subdivided into detection of a physical quantity that also includes its conversion into an electrical signal, preconditioning of the acquired signal, and its digitization. A generic block diagram representing all these steps applicable to most of the medical imaging modalities is schematically depicted in Figure 2.

Image Reconstruction

Image reconstruction is a mathematical process of forming an image using the acquired raw data. For multidimensional imaging, this process also includes a combination of multiple data sets captured at different angles or different time steps. This part of medical image processing deals with inverse problems, which is a fundamental subject of the field. There are two primary algorithms used to solve this type of problems—analytical and iterative.

Typical examples of analytical methods include filtered backprojection (FBP), widely used in tomography; Fourier transform (FT), particularly important in MRI; and delay and sum (DAS) beamforming, a technique which is integral to ultrasonography. These algorithms are elegant and efficient in terms of required processing power and computational time. However, they are based on idealized models and thus have some distinctive limitations, including their inability to handle such complex factors as statistical properties of the measurement noise and physics of an imaging system.

Iterative algorithms overcome those limitations to enable significant improvement in insensitivity to noise and the capability to reconstruct an optimal image using incomplete raw data. Iterative methods typically use a system and statistical noise model to calculate projections based on the initial object model with assumed coefficients. The difference between the calculated projections and the original data defines new coefficients used to update the object model. This procedure is repeated using multiple iteration steps until a cost function, which maps the estimated and true values, is minimized—resulting in a convergence of the reconstruction process to the final image.

There is a large variety of iterative methods including maximum likelihood expectation maximization (MLEM), maximum a posteriori (MAP), algebraic reconstruction (ARC) technique, and many others widely used across medical imaging modalities today.

Image Computing

Image computing deals with computational and mathematical methods operated on reconstructed imaging data to extract clinically relevant information. These methods are applied for enhancement, analysis, and visualization of the imaging results.

Enhancement

Image enhancement refines a transform representation of an image to improve interpretability of the contained information. Its methods can be subdivided into spatial and frequency domain techniques.

The spatial domain techniques operate directly on image pixels, which is particularly useful for contrast optimization. These techniques typically rely on logarithmic, histogram, and power law transforms. The frequency domain methods use frequency transform and are best suited for smoothening and sharpening the images by applying different kinds of filters.

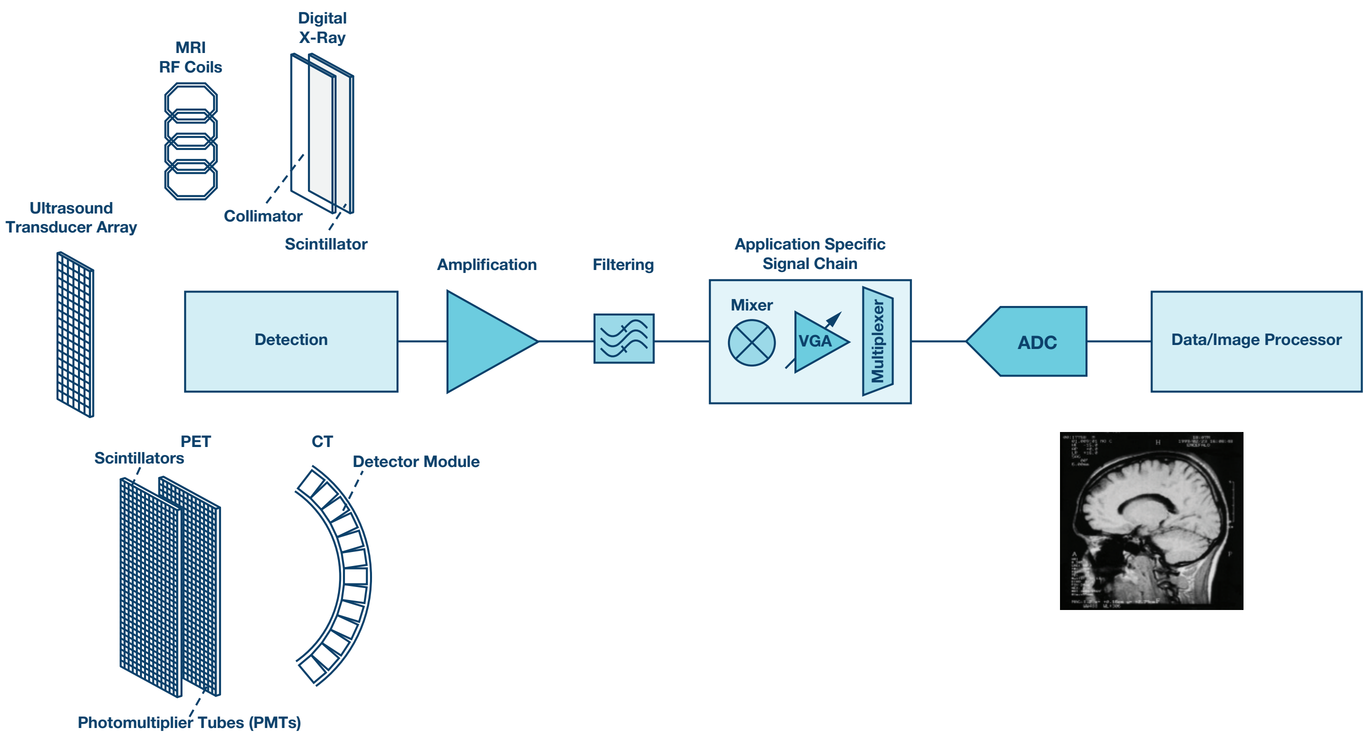

Figure 2. Generic block diagram of the data acquisition process.

Utilization of all these techniques allow for noise and inhomogeneity reduction, contrast optimization, enhancement of edges, elimination of artifacts, and improvement of other relevant properties that are crucial for the subsequent image analysis and its accurate interpretation.

Analysis

Image analysis is the central process in image computing that uses a broad variety of methods which can be grouped into three main categories: image segmentation, image registration, and image quantification.

The image segmentation process partitions the image into meaningful contours of different anatomical structures. Image registration ensures correct alignment of multiple images, which is particularly important for analysis of temporal changes or a combination of images acquired using different modalities. The process of quantification determines properties of the identified structures such as volume, diameter, composition, and other relevant anatomical or physiological information. All these processes have a direct impact on the inspection quality of the imaging data and the accuracy level of medical findings.

Visualization

The visualization process renders the image data to visually represent anatomical and physiological imaging information in a specific form over defined dimensions. Through direct interaction with data, the visualization can be performed both at the initial and intermediate phases of imaging analysis—for instance, to assist segmentation and registration processes, and at the final stage to display the refined results.

Image Management

The final part of medical image processing deals with management of the acquired information and encompasses various techniques for storage, retrieval, and communication of image data. There are several standards and technologies developed to address various aspects of image management. For example, the medical imaging technology picture archiving and communication system (PACS) provides economical storage and access to images from multiple modalities and the digital imaging and communication medicine (DICOM) standard is used for storing and transmitting medical images. Special techniques for image compression and streaming provide efficient realization of these tasks.

Challenges and Trends

Medical imaging is a relatively conservative field where the transition from research to clinical applications may often take more than a decade. However, its complex nature embraces multifaceted challenges on all fronts of its constituent scientific disciplines, which steadily drives continuous developments of novel approaches. These developments represent major trends that can be identified across the core areas of medical image processing today.

The area of image acquisition benefits from innovative hardware technologies developed to enhance the raw data quality and enrich their informational content. Integrated front-end solutions enable faster scan times, finer resolutions, and advanced architectures such as ultrasound/mammography, CT/PET, or PET/MRI combo systems.

Fast and efficient iterative algorithms are increasingly used for the image reconstruction replacing analytical methods. They enable dramatic image quality improvement in PET, X-ray dose reduction in CT, and compressed sensing in MRI. Data-driven signal models are replacing human-defined models to provide better solutions to inverse problems based on limited or noisy data. The main research areas representing the trends and challenges in image reconstruction include modeling of system physics and development of signal models, optimization algorithms, and methods for image quality assessment.

As the imaging hardware captures ever-increasing amounts of data and the algorithms become more complex there is a strong need for more efficient computational technologies. This is a great challenge addressed by more powerful graphical processors and multiprocessing techniques that enable a completely new scale of opportunities for transitioning from research to applications.

The major trends and challenges associated with this transition in image computing and image management encompass numerous topics, some of which are presented in Figure 3.

Continuous developments resulting in novel technologies associated with all these topics narrow the gap between the research and clinical applications and foster the integration of the field of medical image processing into the physicians' workflow to ensure more accurate and more reliable imaging results than ever before.

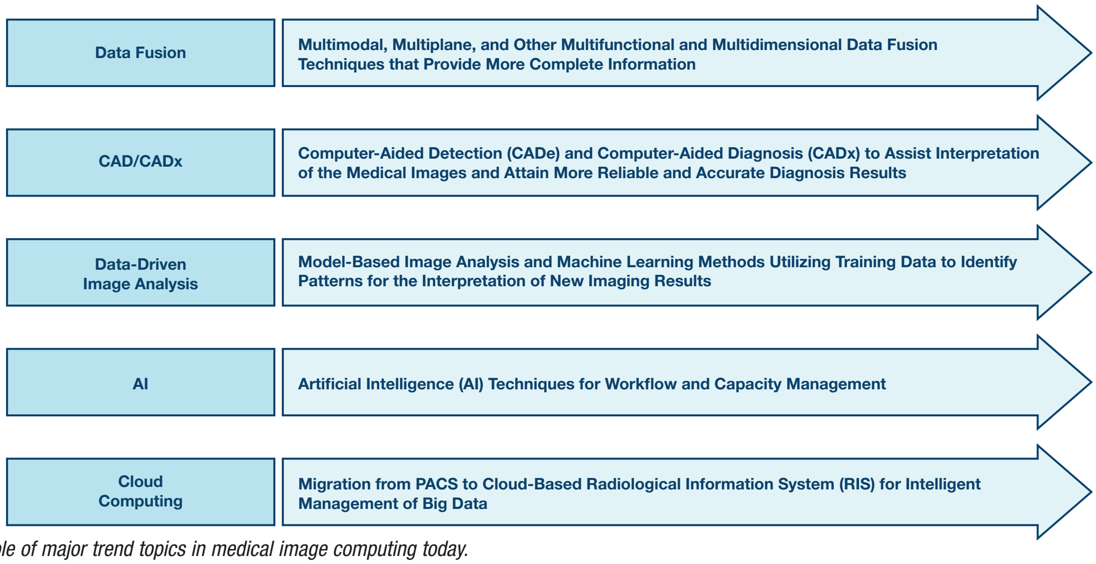

Figure 3. Example of major trend topics in medical image computing today.

Analog Devices offers diverse solutions addressing the most demanding requirements of medical imaging imposed on the data acquisition electronics design in terms of dynamic range, resolution, accuracy, linearity, and noise. Here are a few examples of such solutions developed to ensure the highest level of initial quality of raw imaging data.

A highly integrated analog front-end ADAS1256 with 256-channels is designed specifically for DR applications. Multichannel data acquisition systems ADAS1135 and ADAS1134 with excellent linearity performance maximize image quality in CT applications. Multichannel ADCs AD9228, AD9637, AD9219, and AD9212 are optimized for outstanding dynamic performance and low power to meet PET requirements. A pipelined ADC AD9656 offers outstanding dynamic and low power performance for MRI. An integrated receiver front-end AD9671 is designed for low cost and low power medical ultrasound applications where a small package size is critical.

Conclusion

Medical image processing is a highly complex, interdisciplinary field comprising numerous scientific disciplines ranging from mathematics and computer science to physics and medicine. This article is an attempt to present a simplified but well-structured framework of core areas representing this field with their major subjects, trends, and challenges. Among them is the process of data acquisition being the first and one of the most important areas that defines the initial quality level of raw data used in all subsequent stages of the medical image processing framework.

About the Author

Anton Patyuchenko received his Master of Science in microwave engineering from the Technical University of Munich in 2007. Following his graduation, Anton worked as a scientist at the German Aerospace Center (DLR). He joined Analog Devices as a field applications engineer in 2015 and is currently providing field applications support to strategic and key customers of Analog Devices specializing in healthcare, energy, and microwave applications. He can be reached at *anton.patyuchenko@analog.com*.

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