1. Introduction

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Imaging systems form an integral part of our lives. Research and development efforts in diverse areas of science and technology over the last few decades have resulted in practical imaging systems that we often take for granted today. From cell phone cameras to advanced diagnostic imaging systems, from weather prediction based on satellite imagery to night vision devices meant for soldiers guarding our national frontiers, there are numerous examples of imaging systems that touch all aspects of our lives. Further, in current science and technological investigations dealing with sub-nano to astronomical length scales, imaging systems allow researchers to visualize natural phenomena or objects of interest and in effect, directly contribute to new discoveries. Imaging is thus an active interdisciplinary research area that is relevant to a wide range of fundamental and applied problems.

The chart in Fig. 1.1 shows a wide variety of topics where imaging systems have become indispensable. It may not be too much of an exaggeration to say that every current Science and Technology student is very likely to encounter at least one of the topics listed in this chart during his/her career. While it is difficult to describe all the topics listed in Fig. 1.1 in detail in a single book, luckily for us the various imaging modalities share many common principles and mathematical ideas that are useful for design and analysis of imaging systems. The goal of this book is to present these basic tools followed by a discussion of some specific imaging systems so as to provide the reader sufficient background to enter the area of imaging research.

It is possible to describe a variety of imaging systems schematically by a simple model as shown in Fig. 1.2. A source of radiation

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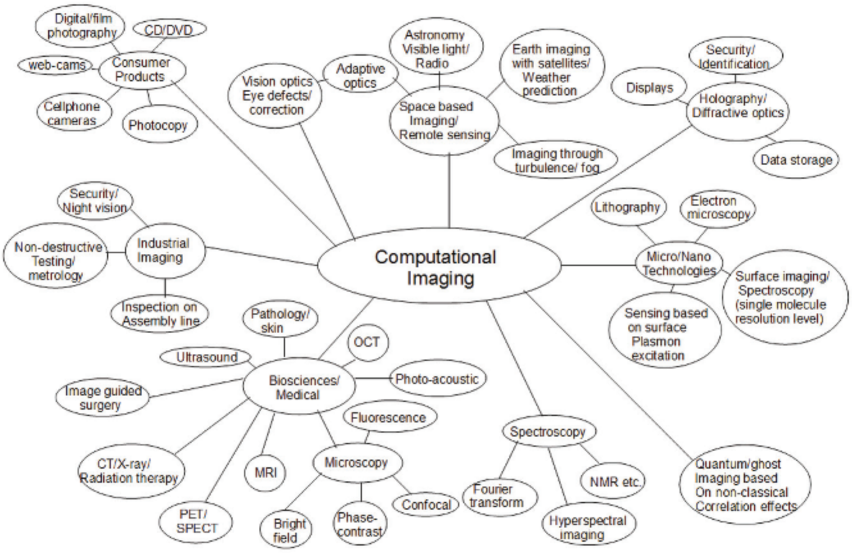

Figure 1.1: Scope of imaging research and development

produces waves (e.g. electromagnetic waves, sound waves) which then interact with the object of interest that is to be imaged. The waves scattered from the object encode the information about the object as space-time variations of intensity, phase, spectrum, polarization, coherence properties, and any other correlations depending on the problem at hand. Note however that this multi-dimensional information in the scattered waves is not available to us directly. The central goal of an imaging system is to derive the maximum possible information that is encoded in the scattered waves so that; a human observer may be able to visualize and interpret this information in the form of an image of the object or its characteristics.

Typically the imaging system hardware (e.g. lens assembly in a camera) is designed so as to modify or manipulate this coded information suitably by applying some transformation to the scattered waves before they are detected at an imaging sensor. Traditional research in imaging systems involved efforts for improving the imaging hardware (e.g. lens design) so as to obtain the best possible visual images at the sensor. With the availability of computer processing power over the last couple of decades, imaging systems (e.g.

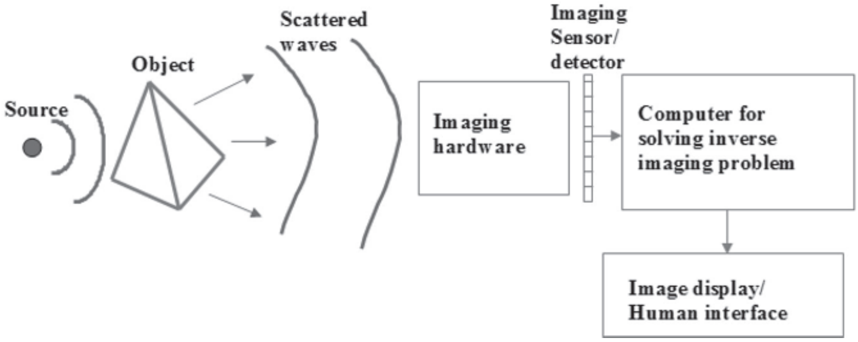

Figure 1.2: Computational imaging model

those in Fig. 1.1) have increasingly become computational in nature. In this new paradigm, the pattern recorded on the sensor may not have any visual similarity to the spatial details of the object of interest to be imaged. The imaging hardware is however designed such that, starting with the digitally recorded data at the imaging sensor, it is possible to solve an inverse or image reconstruction problem and to form an image of the object that is suitable for human interpretation. As imaging systems increasingly become important to scientific investigations and in our daily lives, it is always desirable to have systems with better resolution, faster imaging time, lesser sensitivity to noise, ability to capture multidimensional information (e.g. intensity and spectrum at each pixel) etc. Simple brute force scaling of traditional imaging systems for this purpose may however prove infeasible from technical as well as economic points of view. Computational imaging model has a significant role to play in this context in the future. Computational imaging systems are hybrid in nature as they place equal emphasis on the imaging hardware part and the computational part for solving inverse imaging problems. This opens up new possibilities for obtaining unprecedented imaging performance for years to come. The current trend in various imaging system designs indicates that even the most familiar imaging tools like cameras, microscopes, telescopes, etc. are likely to have a completely different physical form and information gathering capabilities than what we are used to. These developments are exciting because they increase our technological capabilities to probe the nature to newer space-time scales. Some aspects of computational imaging must therefore form a part of training for every serious Science and Technology student.

1.1 Organization of the book

This book is organized in three parts. The first part deals with the Mathematical Preliminaries that will be found useful later the book. This material has been provided in order to make the book self-contained. The mathematical ideas as presented here have not appeared in any single monograph on imaging to the best of the author's knowledge. Discussing the mathematical ideas at the beginning will also help us in setting up a consistent notation for the rest of the book. In Chapter 2 we discuss the important tools of Fourier analysis that are used throughout the book. In Chapter 3 we present the basic ideas behind Shannon sampling theory and the concept of space-bandwidth product which is useful in quantifying information content in an image. The allied topic of the prolate spheroidal functions is also described and an interesting connection between the sampling theory and the prolate functions is discussed. Having introduced Fourier analysis and sampling theory, the next logical topic is the Fast Fourier Transform (FFT) presented in Chapter 4. FFT is an essential tool in almost all image handling tasks. Instead of discussing the finer aspects of the FFT algorithm itself, we present an operational introduction to this topic which will help a reader to use FFT functions available in several standard numerical software packages effectively for simulating optics and imaging problems. Linear systems theory and associated inverse problems are essential for understanding the basic working principle of computational imaging systems. These topics are described in detail in Chapter 5. Several current computational imaging systems require image reconstruction methods that cannot be described as linear filtering operations but rather as constrained optimization problems. Some basic ideas in constrained optimization are described in Chapter 6. This chapter also includes more advanced topics such as compressive imaging that are likely to play major role in future imaging system designs. The last Chapter of the first part presents a discussion of random processes. Conceptual treatment of imaging systems is often presented by means of deterministic equations. The generation, propagation and detection of light waves are however inherently statistical in nature. The understanding of random processes is therefore essential for taking up any imaging system design problem. The topics discussed here find direct utility in later parts of the book.

The second part of the book discusses some important concepts in Optics that are key to understanding the working of imaging systems and their capabilities or limitations. Unlike many well-known books in Optics, the topics in this part are not covered from a historical perspective but are presented in a way that is more suitable for developing an understanding of imaging phenomena from a systems perspective. We begin this part with description of essential concepts of ray or geometrical optics in Chapter 8 followed by details of wave equation and diffraction phenomena in Chapter 9. Diffraction theory is essential to understand how light waves can carry information from the object of interest to the imaging system. Chapter 10 presents another view of diffraction from a transfer function approach. The exact Rayleigh-Sommerfeld-Smythe relations for description of diffraction problem are also presented in this chapter. Next in Chapter 11 we discuss some useful approximations to the exact diffraction relations, viz. Fresnel and Fraunhoffer approximations, that are found to be useful in analysis or design of several common practical system setups. The important ideas related to coherence of light fields are described in Chapter 12. While the reader may not appreciate the reason for discussing this topic at this stage, the author believes that without the knowledge of coherence theory, one's knowledge of Optics is incomplete. This is especially so if someone is interested in designing novel futuristic imaging systems. This discussion is followed by Chapter 13 on polarization of light. Polarization is an additional degree of freedom possessed by light waves, although it has not been utilized to its fullest potential in imaging system design so far. Next in Chapter 14 we use the ideas developed in second part of the book to show the reader how one can model simple optical systems involving free-space propagation, lens elements or other phase masks. After covering the important cases of the optical Fourier transform and the canonical or 4F imaging systems configurations, we discuss several practical systems that utilize these ideas. Concepts that help one evaluate an imaging system performance such as the Optical Transfer Function (OTF) are also discussed. Chapter 15 which is the last chapter of the second part of the book presents a general treatment of imaging phenomena from an information point of view. A simple treatment based on the sampling theorem is used here to provide some interesting insights into information carrying capacity of imaging systems from object to the image space.

The third part of the book builds on the material developed in the first two parts to discuss some specific computational imaging ideas. This part is intended to give the readers a feeling for the current research ideas in computational imaging. In Chapters 16 and 17 we discuss one of the most important computational problem of interferometric and non-interferometric phase imaging. Phase of light waves scattered by an object encodes critical information about the object. The phase information is however not available to us directly and phase can only be inferred computationally. In Chapter 18, we discuss some novel compact multi-lens systems that outperform traditional cameras by combining unconventional design and computational image recovery. In Chapter 19 we describe some phase mask designs that use pupil function engineering for extended depth of field imaging. Microscopic imaging beyond traditional diffraction limit has become essential part of basic Bio-sciences research and we discuss a powerful computational imaging modality that uses structural illumination for super-resolution imaging in Chapter 20. In Chapter 21 we present some basic ideas in image reconstruction from projections - a topic which is of considerable importance to the working of several diagnostic imaging systems. Finally in Chapter 22 we describe a somewhat unusual imaging system setup that uses a single pixel detector for generating high resolution images exploiting the correlations in specially designed optical beams.

While computational imaging systems other than optical imaging systems do exist, the author believes that having studied this material, a reader will have no difficulty in understanding them. The material covered in the first two parts in and some selected topics from the third part, can constitute sufficient material for a semester-long course suitable for academic programs in Optics/Photonics.