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Introduction

Microwave (300 MHz to 30 GHz) and millimeter-wave (30–300 GHz) imaging (MMI) technologies exploit electromagnetic (EM) waves with much lower frequencies than the visible light. This allows for sufficient penetration into various dielectric materials for inspection purposes and the ability to "see" through media which cannot be inspected via optical or acoustic means. These technologies have underwent rapid growth during the last few decades due to a steady demand for new applications and services along with remarkable miniaturization and diversification of the high-frequency electronics. This has resonated well with the significant developments in computing technologies and processing algorithms leading to a wide range of applications such as imaging various composites, cement, soil, wood, ceramics, plastics, clothing, living tissues, etc.

Another major motivation to develop these technologies is that the microwave and millimeter-wave radiation is nonionizing and is not considered hazardous at moderate power levels. This makes such technologies favorable compared to the competing X-ray imaging technology which is ionizing, i.e. it has enough energy to potentially cause cellular and DNA damage or to elevate the risk of developing cancer in living tissues [1].

Moreover, the possibility of measuring wideband data as well as acquiring both phase and magnitude (which is typically challenging at frequencies higher than microwave and millimeter-wave) makes these technologies favorable for three-dimensional (3D) imaging applications, e.g. see [2]. All the aforementioned advantages have motivated the researchers in academic and industrial institutions to pursue development of the microwave technologies toward various imaging and sensing applications.

Figure 1.1 illustrates a typical MMI system consisting of a transmitting antenna illuminating the inspected medium. The inspected medium includes the background along with any objects that are electrically sufficiently different

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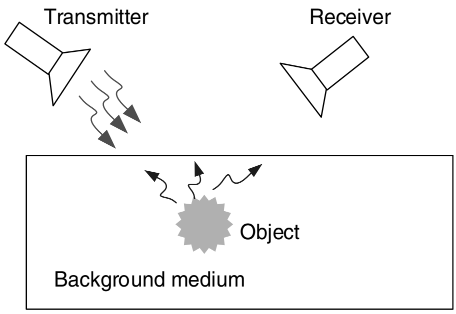

Figure 1.1 Illustration of a MMI setup. The object inside the background medium scatters the EM waves emitted by the transmitter provided its electrical properties are different from those of the background. Some of the scattered waves are picked up by the receiving antenna and are processed to detect the object.

from the background to cause scattering of the EM waves. The scattered waves due to the presence of the object along with the scattered waves due to the background medium are acquired by a receiving antenna. The acquired data are then processed to reconstruct two-dimensional (2D) or 3D images of the object.

In various MMI systems, the transmission and reception can be implemented by the same antenna (monostatic system), or one antenna can transmit while another receives (bistatic system), or an array of antennas (multistatic) can receive the back-scattered waves. Besides, the data acquisition can be implemented while the antennas are stationary or the antennas may perform scanning of the back-scattered waves over an aperture to construct a synthetic aperture. An alternative solution to avoid mechanical scanning of the antennas (that may be time-consuming and may suffer from positioning errors) is the use of stationary antenna arrays that can be switched electronically to capture the distribution of the back-scattered waves over an aperture.

1.1 Some Emerging Applications of MMI

Some of the applications of microwave imaging technology, such as synthetic aperture radar (SAR) [3] and ground penetrating radar (GPR) [4], have been well-established, commercialized, and employed for several decades. These technologies provide high-resolution qualitative images of the earth surface, landscape, weather condition, underground objects, hydrocarbon reservoirs, etc. These have been typically long-range applications of MMI since the distance between the imaged objects and the antennas (sensors) is typically much larger than the operation wavelength.

Recently, researchers have been pursuing the capabilities of MMI in some new applications, demonstrating promising imaging results. These new applications, such as concealed weapon detection [5], nondestructive testing (NDT) [6], through-the-wall imaging [7], and biomedical imaging [8], are under rapid development and commercialization. Their success depends on how they can overcome challenges encountered by the competing technologies of ultrasound imaging, X-ray imaging, magnetic resonance imaging (MRI), etc. in each particular application domain.

The conventional MMI techniques such as SAR and GPR suffer from the well-known "diffraction limit" in the resolution. The diffraction limit states that the spatial resolution of the far-field techniques is proportional to the operation wavelength, i.e. the shorter the wavelength, the smaller the size of the shapes that can be resolved in the image. However, near-field MMI techniques may offer better spatial resolution which is typically proportional to the sensor's sensing dimensions (e.g. see [9]). This is due to the use of evanescent waves, which contain information about finer details of the object but decay exponentially versus the distance between the object and the antenna. Thus, while using the evanescent-wave information is possible in the near-field MMI applications (leading to better spatial resolution), in the far-field, receiving the evanescent waves is practically impossible leading to degradation of the spatial resolution down to the diffraction limit. Later in this book, we discuss the resolution of MMI systems in more detail.

The case of interest in the recent applications of MMI is that of an object in the near field of the antenna. This necessitates the development of new algorithms and techniques for image-reconstruction purposes. In the following, we briefly describe the recent progress in some of the emerging and most promising applications of MMI technologies which are mostly mid-field to near-field applications.

One revolutionizing application of the MMI is in security screening in public places such as airports. This technology allows for penetration of the EM waves through clothes and for the formation of a whole-body image of the scanned person in order to seek for prohibited concealed items [5, 10–13]. So far, several countries have chosen scanners based on this technology for security screening in the airports [14] over the competing technology, which is back-scattered X-ray. These millimeter-wave scanners can be divided into two categories: active and passive. Active scanners illuminate the inspected domain with millimeter-wave energy and then measure and process the reflected energy for image reconstruction [5, 11–13]. Passive systems create images using only the millimeter-wave spectrum of the ambient thermal radiation and that emitted from the inspected body [15–17].

Figure 1.2 shows a millimeter-wave imaging setup used by transportation security administration (TSA) in the US airports for whole-body scanning. This figure also shows some sample reconstructed images by this system. It is worth noting that the resolution of the produced images using millimeter-wave technology in the airport security screening is so high that it has raised privacy concerns. This has led to the prohibition of displaying detailed images by the US congress and applying automatic target recognition software (which provides a generic body outline with largest contrasts due to the concealed prohibited

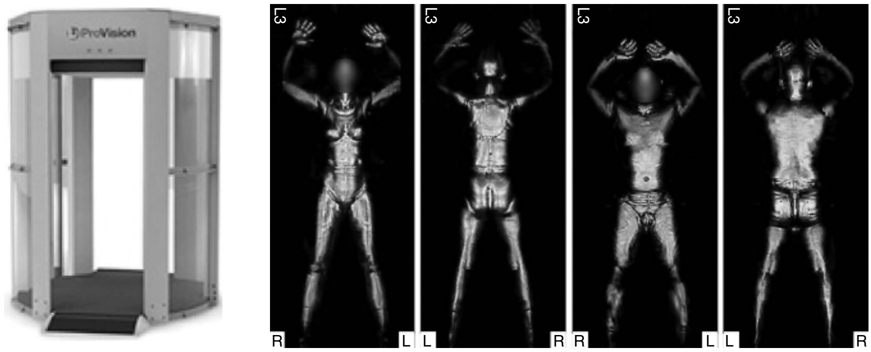

Figure 1.2 (a) Millimeter-wave whole body scanning setup based on the technology developed for airport security screening. (b) Sample images of screened persons. *Source:* Reprinted with permission from [14].

objects). This is to emphasize that very high-resolution, robust, and accurate images can be captured using this technology.

Another application of the MMI, which is under active research in the microwave society, is in biomedical imaging [18]. This includes imaging of isolated organs or *in situ* imaging such as imaging of the brain for stroke detection [19–21], cerebral edema [22], breast cancer [8, 23–25], bone imaging [26, 27], heart imaging [28–33], and joint-tissue imaging [34]. In these applications, the tissue is illuminated with low-power microwaves which are safe and allow for frequent examinations. The scattered waves are then measured and processed to provide images of the interior of the tissue. The images show various tissues such as muscle, fibro-glandular and fatty tissues, which exhibit various contrasts in the dielectric properties. This provides a basis for distinguishing the normal tissue from the malignant tissue (tumor). The malignant tissue typically has larger dielectric properties compared to normal tissue due to the higher concentration of blood vessels and water content. Figure 1.3 shows the measurement setup for brain imaging using a physical head phantom and the Vivaldi antenna proposed in [35]. This figure also shows the reconstructed images using the confocal method showing damage due to stroke at two different locations.

Biomedical microwave imaging is proceeding fast to make an entrance in the highly competitive world of medical imaging. Recently, there have been start-up companies that are commercializing the microwave tissue imaging technology such as EMTensor [36] and Medfield Diagnostics [37] for stroke diagnosis, and Micrima [38] for breast imaging.

In general, the biomedical imaging technology based on MMI offers advantages such as low health risks, ease of mobility due to compactness, relatively good resolution, and cost effectiveness. However, it often lacks the spatial

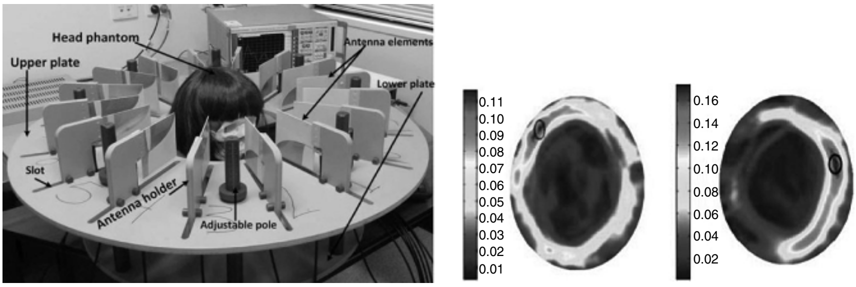

Figure 1.3 (a) Measurement setup for brain imaging using a physical head phantom and the Vivaldi antenna. (b) Reconstructed images using the confocal method showing position of stroke at two different locations. The true position of the stroke is shown by an ellipse. *Source:* Reprinted with permission from [35].

resolution that may be required for some applications. Presently, its spatial resolution is inferior compared to that of computed tomography (CT) or MRI. The success of MMI technologies in the biomedical field depends on the capability to address the technical and commercial challenges faced by the competing technologies. One major challenge in this area, which is currently under intensive investigation, is the relatively high error rate that can occur when the electric contrast between malignant and healthy tissues is not sufficiently large, as in the case of tumors in fibro-glandular tissue or muscle [39, 40]. This dramatically reduces the specificity of a microwave-based diagnosis. Arguably, this may be the main challenge in applications such as breast cancer screening, since most of the breast tumors are located in this kind of tissue. To overcome this problem, the use of contrast agents such as carbon nanotubes [41] and magnetic nanoparticles [42–46] is gaining attention. In particular, the use of magnetic nanoparticles has been under investigation to take advantage of their specific features compared to dielectric contrast agents [42]. These particles have been approved for clinical use and can be manipulated properly so that they can specifically target the malignant tissues. One important feature is that their response in the microwave regime can be properly changed by applying an external polarizing magnetic field. This external field does not change the response of the normal tissue which has not been targeted by these particles. As a result, by exploiting a proper differential measurement strategy, one can separate the response of the normal tissue from that of the malignant tissue targeted by the magnetic nanoparticles [42]. The feasibility of this technique has been investigated and has demonstrated promising results in simulations and preliminary experiments.

The last important application of MMI that is discussed here is the NDT of nonmetallic media for integrity inspections. NDT based on MMI involves developing sensors/probes, methods, and calibration techniques for detection of flaws, cracks, defects, pits, voids, inhomogeneities, moisture content (MC), hidden artifacts, etc. by means of microwaves and millimeter waves [6, 47]. Such technology is increasingly being used for quality control and condition assessment of various dielectric materials with the following diverse objectives: detection and sizing of fatigue cracks in metal surfaces including those hidden under paint and dielectric coatings [48], detection and evaluation of corrosion under paint and composite laminates [49], defect evaluation in various composite structures [50], evaluation of the composites [6, 47], and microwave microscopy [51].

A major emerging application of MMI is the inspection of composite materials. These materials are replacing many industrial metallic components due to being lighter, stiffer, stronger, and more durable. Composite materials cannot be inspected by the conventional NDT techniques such as eddy current or magnetic flux-leakage measurements which can only be employed for inspection of metallic structures. On the other hand, MMI techniques are well-suited for testing these materials since microwaves and millimeter waves can easily penetrate low-loss dielectric media. In fact, in many cases, MMI could be the only technology that can be employed for integrity inspections. In some other cases, it could be combined with other NDT techniques such as ultrasound imaging to provide a more comprehensive inspection. A good review of microwave and millimeter-wave NDT techniques has been provided in [52]. Figure 1.4

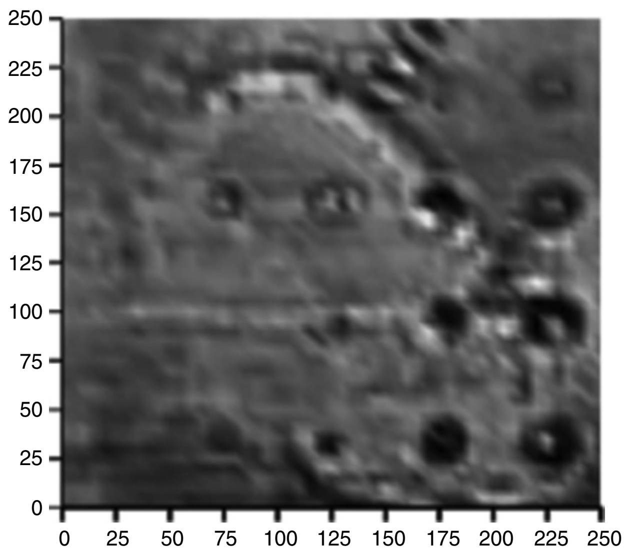

Figure 1.4 Sample millimeter-wave image of a shuttle external fuel tank's spray-on-foam insulation (SOFI) at 100 GHz using a horn antenna [50].

shows a sample millimeter-wave image of a shuttle external fuel tank's spray-on-foam insulation (SOFI) at 100 GHz using a horn antenna [50].

In general, MMI offers several advantages over other NDT methods such as radiography, ultrasonics, and eddy currents [52]: relatively low cost, good penetration in dielectric materials, good resolution especially in near-field applications, contactless feature of the microwave sensor (antenna), no need for a couplant to transmit the signal into the material under test (unlike ultrasonic methods), monostatic, relatively low power, compact, easily adaptable to existing industrial scanners, real time, no need for operator expertise in the field of microwave engineering, robust, rugged, and repeatable. Given the outlook for the rapid and steady growth of incorporating composite materials in a wide range of structures (replacing metallic components), the future of microwave and millimeter-wave NDT is very promising.

1.2 Quantitative Versus Qualitative MMI

In terms of the accuracy of the reconstructed images, MMI techniques can be classified as either quantitative or qualitative. These techniques vary significantly with regard to the hardware components, data acquisition schemes, and processing algorithms. The reader is referred to [53] for a comprehensive review of various MMI techniques.

In quantitative imaging techniques, which are also commonly referred to as inverse scattering methods or optimization-based methods (e.g. see [54]), the aim is to provide an accurate estimation of the electrical properties of the imaged objects. This is accomplished by solving a nonlinear inverse problem. Such solution is typically expensive to evaluate in terms of both memory and time. Thus, although these techniques provide more accurate images of the inspected media, they are not practical for real-time applications such as object tracking or tissue imaging in which the fast motion of the object or patient, respectively, may create artifacts. In quantitative imaging techniques, the nonlinear inverse problem can be converted into a linear inverse problem by using the Born or Rytov approximations [55]. Despite the fact that direct matrix inversion methods can be employed to solve the reconstruction problem, this can be costly when the size of the problem (number of voxels in the inspected domain) is large. To overcome this problem, direct inversion of the relevant matrix is replaced with iterative solvers [56–64]. These techniques are also usually slow and not practical for real-time imaging applications.

It is worth noting that recently two direct quantitative imaging approaches have been proposed [65]. One is based on the scattered-power maps [53, 66, 67]. The second one exploits the principles of microwave holography [68]. The accuracy and the applicability of these methods are limited due to the fact that, as any other linear-inversion method, these methods are based on a linearized model of scattering. Their advantage is that they are fast and capable of providing images in real time. Both methods rely on the use of quantitatively accurate point-spread function (PSF), i.e. the PSFs must not only represent the normalized magnitude and phase distribution of the response to a point scatterer but also they have to scale properly, in a complex sense, with the complex contrast of the point scatterer. Quantitatively accurate PSFs can be acquired via calibration measurements. The closer the background medium in these measurements is to the averaged electrical properties of the imaged object, the better the quantitative output would be since the method remains rooted in a linearized model of scattering. In far-zone measurement scenarios, "normalized" PSF approximations such as the plane-wave and the isotropic-wave approximations could also be used. These can be additionally improved if the antenna radiation pattern is employed to correct the field distribution. Such approximations eliminate the need to perform calibration measurements and would, therefore, save time.

In theory, the advantage of quantitative optimization-based techniques is that they are capable of accurate estimation of the contrast function of the imaged object. However, in practice, these techniques suffer from serious challenges such as complexity, prohibitive memory, and time requirements, as well as ill-posedness of the solution. In particular, the solution is typically sought in an iterative manner in which at each iteration a 3D forward EM problem needs to be solved. This is very time-consuming and makes the use of these techniques in real-time imaging applications almost impossible (considering the current limitations of the computing technology). In contrast, most qualitative techniques often provide less accurate images but are much faster. Typically, by applying proper simplifying assumptions on the scattering model, these techniques seek an approximate solution to the inverse scattering problem that can be as fast as a fraction of a second even with tens of thousands of voxel contrast values. In these techniques, a qualitative profile (which is referred to as reflectivity function, qualitative image, or contrast function) is reconstructed. The aim is to estimate the position, the shape, and the spatial extent of an object whereas its contrast with respect to the background medium may be estimated only approximately, often in the form of a normalized image of the reflectivity.

The qualitative MMI techniques can be categorized into time-domain imaging (e.g. see [69]), diffraction tomography (DT) (e.g. see [70]), sensitivity-based imaging [71], and holography (e.g. see [72]). In general, most of these techniques use radar concepts to generate a qualitative reflectivity image in order to differentiate the object from the background. The objects are usually stronger scatterers than the background medium. In the following, we briefly review these techniques.

The time-domain imaging systems operate based on the radar signal-processing principles in which the inspected medium is illuminated with wide-band pulses and the back-scattered pulses due to the presence of the object are measured. Various data collection schemes have been employed according to the specifics of the application such as stationary antennas or antennas that scan over an aperture to construct a synthetic aperture. The acquisition technique where the radar collects data over a line or a surface is referred to as SAR. Nowadays, time-domain imaging systems use ultra wideband (UWB) pulses, i.e. the pulses may cover a wide frequency band all the way from 100 MHz to about 10 GHz. The UWB radar is a rapidly growing technology which holds enormous potential for further applications in detection, imaging, and guidance [73, 74].

DT emerged in the late seventies and the eighties mainly in the fields of acoustics and microwave imaging as an alternative to the straight-ray tomography developed for X-ray imaging. Its principles are closely related to those of the holographic reconstruction. It could be considered as a generalization of the conventional straight-ray tomography used in X-ray CT. Unlike X-rays, acoustic and EM waves do not travel along straight paths. This is because the components of the imaged objects are often comparable or smaller than the wavelength. The inversion in X-ray tomography is based on the Fourier Slice Theorem, which assumes a straight-path propagation model. Generally, such model cannot be applied in acoustics or microwave imaging. Instead, when the wavelength is long, an alternative method called Fourier Diffraction Theorem is employed to reconstruct a 3D image of the object [75]. It can be shown that the Fourier Diffraction Theorem reduces to the Fourier Slice Theorem when the wavelength tends to zero [75]. The Fourier Diffraction Theorem employs the linearized scalar Born model of scattering. It also assumes a plane-wave illumination and point-like receiver antennas. Plane-wave illumination of the whole imaged region is not easy to implement at microwave frequencies, especially in the near-field imaging problems. Thus, the need to place the object in the far zone of the microwave source is a serious limitation in DT. Due to this reason, DT is not convenient for near-field imaging applications such as tissue imaging [76–78]. Besides, to implement DT, the receiver antennas must closely resemble point-wise omnidirectional probes. This is also not practical in near-field imaging. Due to such limitations, DT has not made much progress in terms of real-world applications, in particular, for near-field imaging of dielectric bodies.

Another qualitative MMI technique is sensitivity-based imaging that was first proposed in [79, 80] as a detection method. Its spatial resolution and robustness to noise was later studied in [71]. It employs frequency-domain responses and it can be configured to work with complex-valued responses, or with magnitude and phase responses separately, depending on which is available. In far zone reflection (back-scattered) measurements, it is the phase that carries most of the information about the object and its availability is critically important. In the extreme near zone measurements, back-scattered or forward-scattered, magnitude-only data may suffice. A far zone scenario where magnitude-only data may be sufficient arises in the imaging of lossy objects where the signal attenuation is the decisive factor shaping the signal. This imaging technique has been extended to quantitative imaging as described earlier.

The last qualitative MMI technique described here is holographic imaging which dates back to the early 1970s when the original optical holography developed in [81, 82] was extended to longer wavelengths at microwave frequencies [83–85]. Almost at the same time, similar approaches were developed for acoustic holography. In all three areas (optics, acoustics, and microwaves) the amplitude and phase of a wavefront scattered from the inspected object is captured first via recording a hologram. The sampled wavefront is then "reconstructed" either optically or by using Fourier-optics-based computer image-reconstruction algorithms. Acoustic and microwave holography are well suited to digital computer image reconstruction since the data are typically sampled by a scanned transceiver, and the relatively long wavelength allows for reasonable data size when fulfilling the Nyquist sampling criterion.

The modern holographic MMI techniques were originally proposed for concealed weapon detection. They used far-field approximations for the illuminating and back-scattered waves along with point-wise transmitter and receiver antennas. However, these techniques have been developed further in recent years to provide more accurate imaging results for near-field applications and for large transmitter and receiver antennas. These developments expand the range of applications for holographic MMI techniques significantly. For instance, they can be employed to realize real-time 3D imaging of the tissues with higher accuracy. Various data acquisition configurations have been developed for holographic MMI based on the rectangular apertures (e.g. see [5, 86, 87]), cylindrical apertures (e.g. see [11, 88, 89]), and manually selected and nonuniformly distributed measurement positions [90].

1.3 Advantages of Holographic MMI Techniques

For real-time 3D imaging of dielectric bodies, as described earlier, the quantitative imaging techniques are often not practical due to the huge memory and time requirements. While the qualitative techniques are faster, they suffer other drawbacks mostly with regard to the accuracy of the generated images. This is due to the simplifying assumptions made to expedite the solution of the inverse scattering problem. Some of these approximations include: (i) assuming point-wise transmitter and receiver antennas, (ii) assuming locally plane-wave form for the illuminating and back-scattered waves, and (iii) using the linear Born approximation which implies that the field inside the object is approximated with the incident field, i.e. the field that would be observed in the absence of the object.

Recently, holographic imaging techniques have been developed to address the first two issues. These techniques can now take into account the physical structure of the antenna and its effect on the produced incident field. These are of crucial importance when using MMI techniques for near-field imaging applications such as tissue imaging or NDT. In this book, we review the breakthrough developments in holographic MMI, which have paved the way toward practical real-time 3D imaging in both far-field and near-field applications.

1.4 Chronological Developments in the Holographic MMI Techniques

Holographic MMI techniques were originally rooted in the concepts derived in the optical regime but some of the later developments showed their close resemblance to the SAR imaging methods. Here, we describe how holographic MMI techniques emerged and evolved along a path toward similarity with SAR imaging and how they were further extended for near-field applications.

The holographic imaging concept was originally introduced in the field of optical imaging when Gabor [81, 91] aimed at improving the images obtained by electron microscope although he demonstrated the feasibility of his method with light waves. For this purpose, he demonstrated the possibility of acquiring the magnitude and phase of a wave as an interference pattern formed by this wave and a known reference wave. He also developed the mathematical foundations for the image reconstruction from such interference patterns. A review can be found in [92]. Gabor's experimental setup was improved by Leith and Upatnieks [82, 93] in the early sixties to achieve higher quality images. The work of Leith and Upatnieks resonated well with the availability of lasers leading to a new generation of 3D imaging systems. The progress in the field of optical holography inspired researchers in other fields, in particular acoustics [94–96], to use similar concepts for imaging optically opaque objects. In other words, while in the original optical holography the aim is to reproduce the optical perception of a 3D object from its recording, i.e. when the object is no longer available for viewing, in acoustic holography the objective is to produce an image of an object which is embedded inside an optically obscured medium. Despite this difference, the principles of producing an image are common between optical and acoustic holography.

Microwave holography was developed almost at the same time as acoustical holography [97–101]. Similar to acoustical holography, microwave holography aims at the image reconstruction of optically opaque objects. Thus, in this early stage, microwave holography closely resembled the optical method for data acquisition referred to as the "recording step" and that for the image reconstruction referred to as "reconstruction step" [102, 103]. In the recording step, an intensity pattern (hologram) is formed from the interference pattern between the scattered wavefront and a coherent plane-wave, introduced at an offset angle to the recording plane. This offset hologram was first introduced by Leith and Upatnieks [82], for the recording of optical wavefronts. In an optical hologram, the record is imprinted on a photographic plate (the recording medium). In microwave holography, this could be the intensity pattern acquired through the scanning of an antenna over the acquisition plane, the antenna being connected to a simple diode detector (a receiver that measures only the signal intensity) [85].

The subsequent progress in the field of holographic MMI can be divided into two separate paths: indirect holography and direct holography. What is common between these two categories of techniques is that both exploit the magnitude and the phase information of the back-scattered waves in order to generate images and to achieve resolution enhancement compared to the images obtained from raw amplitude measurements only.

The indirect microwave holography has been in fact the extension of the early work on this topic. It has the most resemblance to optical holography in terms of recording of a hologram. The major advantage of indirect holography is that it does not require the use of expensive vector-measurement equipment to obtain the complex field scattered from the imaged object. Instead, the phase information is mathematically recovered from low-cost intensity-only scalar microwave or millimeter-wave measurements. This simplifies the hardware implementation and reduces the cost of the imaging system. In the literature, indirect microwave holography was proved to have a significant potential to be employed in the measurement of complex antenna near-field and far-field radiation patterns [104, 105]. Recently, this technique has been extended to the imaging of early-stage breast cancer tumors [106] and metallic objects [107]. Although promising results have been achieved in [106, 107], the reconstruction of the scattered field was limited to the measurement plane. In [108], this issue has been addressed by back-propagating the reconstructed scattered field at the measurement plane to the plane of the imaged object.

The direct holographic MMI techniques, however, use radio frequency (RF) circuitry or vector network analyzer (VNA) to record both the magnitude and phase of the back-scattered waves directly. Although, similar to recording a hologram in indirect holography, measurements are typically performed over an aperture (plane), the scattered waves are sampled in complex form (unlike the recording of scalar values for capturing a hologram in indirect holography). As the direct holographic algorithms developed, their resemblance to SAR-based imaging methods became evident. Currently, the terms SAR imaging and direct microwave holography are being used to refer to reconstruction approaches that are mathematically very similar, in particular, for far-field imaging applications. In both, exploiting the phase information is at the heart of the image generation. The difference is usually in the dimensionality of the problem. SAR works with the wideband radar data acquired on a line. The location of the imaged surface is known. Thus, SAR methods reconstruct a 2D image of the object reflectivity on this known surface. In contrast, direct microwave holography works with wideband data acquired on a surface which enables the reconstruction of a 3D image. In particular, the proposed direct holographic technique in [5, 11] merges the single-frequency 2D holography with wideband 2D SAR to achieve 3D imaging. Wideband back-scattered signals are collected over a rectangular [5] or cylindrical [11] aperture. The processing relies on an assumed analytical (exponential) form of the incident field and the Green function to cast the inversion in the form of a 3D inverse Fourier transform (FT). An improvement of this imaging approach has been presented in [90] where the nonuniform manual scanning has been proposed as a practical imaging method.

In [86, 109, 110], the direct 3D holography technique was extended to near-field imaging. In this case, the analytical approximations of the incident field and the Green's function are inadequate; this is why numerical models are employed instead, which better represent the particular acquisition setup and antennas. The method proposed in [86, 109, 110] also allows for incorporating forward-scattered signals in addition to the back-scattered signals acquired on two opposite planar surfaces. The processing involves the solution of a linear system of equations for each spatial frequency pair (k_x, k_y). Then, 2D inverse FT is applied to the solution on planes (slices) at all desired range locations. The advantage of this approach is that the linear systems of equations have much smaller dimensions and are less ill-conditioned compared with the systems of equations arising in optimization-based imaging techniques. Furthermore, the resampling of the data in k_z-space is avoided. The assumption that k_x, k_y, and k_z are independent variables, which leads to errors in the image reconstruction process, is also unnecessary since the use of the parameter k_z is avoided altogether. It is important to note that in [109, 110], the role of the back-scattered data in 3D holographic imaging with planar scanning is emphasized, particularly with regard to the range spatial resolution. This is relevant in the imaging of lossy dielectric mediums such as tissues where the back-scattered data are of much poorer signal-to-noise ratio (SNR) compared with the forward-scattered data, resulting in loss of range resolution. In the near-field holographic imaging [86, 109, 110], the data for the incident field and the Green function are obtained via simulations. In practice, often, the fidelity of the simulation models, although better than the analytical approximations, may still be too low to ensure good image quality. The fidelity of the simulation model can be assessed through its ability to reproduce the measurements of known objects performed with the particular imaging setup. One factor contributing to the low fidelity of the simulations in near-field imaging can be the numerical errors such as those due to a coarse discretization mesh or imperfect absorbing boundary conditions. Such errors however, are not the major concern because they can be reduced by mesh refinement and stricter convergence criteria for the numerical solution. Unfortunately, this may also lead to prohibitive computational burden. The major concern in near-field imaging is in the so-called modeling errors which are much more difficult to reduce. These errors are rooted in the inability to predict all influencing factors arising in the practical implementation of the acquisition setup. These include: fabrication tolerances of the antennas and the positioning components, uncertainties in the constitutive parameters of the materials (especially the absorbers) used to build the measurement chamber, deformations due to temperature or humidity, and so on. In addition, models often ignore complexities in the cables, the connectors, the fine components of the measurement chamber (e.g. screws, brackets, thin supporting plates), and so on. In [87], a method has been proposed to acquire the incident field and the Green's function specific to the particular acquisition system via measurements of a known calibration object (CO). The method exploits the concept of PSF of a linear imaging system where the response due to an arbitrary object is the convolution of the response due to a point-wise scatterer (the scattering probe) with the spatial variation of that object.

1.5 Future Outlook for Holographic MMI for Real-Time 3D Imaging Applications

The authors of this book believe that direct holographic MMI provides a powerful and robust means for practical real-time 3D imaging and is projected to grow rapidly in the coming years. The main driving force behind this growth is both the demand for inspection and imaging of media for which MMI is the best method of choice. It is envisioned that this growth will be boosted even further due to the unprecedented miniaturization of the radio-frequency hardware as well as the recent progress in the processing algorithms for the near-field imaging applications.

On the hardware side, the size and the cost of the hardware needed to perform microwave sensing has dramatically decreased with the advent of the radio-on-a-chip (RoC), the on-chip software-defined radios (SDR), and the single-chip radars operating well into the 70-GHz bands. Coherent signal measurements with amplitude and phase information are now possible with electronic circuits occupying areas less than a square centimeter and with a price that ranges anywhere between tens and several hundreds of dollars. Multiplexing hundreds even thousands of microwave sensors through digital control is within reach allowing for bypassing the expensive and bulky RF switching and power-distribution networks. As a result of these advancements, large arrays of microwave sensors which are capable of sampling the back-scattered wave in complex form (acquisition of both magnitude and phase) are now affordable.

On the processing side, the availability of fast, robust, and accurate algorithms encourages the use of direct holographic MMI technology for many new applications, in particular, those for which the imaged object is in the near-field of the sensing antennas. To the best of our knowledge, there is no other MMI technique that can offer all the advantages of near-field direct holographic MMI techniques including: (i) being fast and robust, (ii) take into account the physical size of the antennas and their near-field, and (iii) taking advantage of the evanescent waves in the near-field of the imaged object to achieve the highest cross-range resolution.