1. On the Role and the Exploitation of the Information in Inverse Scattering Problems for Microwave Imaging Theory, Numerical Tools, and Applications

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Abstract: *Ill-posedness and non-linearity are paramount issues to be carefully addressed when solving inverse scattering problems (ISPs) arising in several microwave imaging (MI) scenarios. Such issues are highly correlated to the limited amount of non-redundant information retrievable from the scattering data. Accordingly, reliable, robust, and computationally-efficient solutions can be obtained by seeking approximate guesses satisfying additional constraints derived from different/additional sources of information, when these are available. In this framework, this chapter is aimed at reviewing some of the most effective and innovative strategies for the exploitation of different sources to recover information and yield faithful and reliable ISP solutions in many practical MI scenarios.*

1. Introduction

Microwave imaging (*MI*) aims at retrieving the physical and/or geometrical features of one or multiple unknown targets embedded within an inaccessible domain by processing its electromagnetic (*EM*) signature when illuminated by a set of external probing sources [1][2]. During the last decades, several *MI* techniques have been proposed with applications ranging from free-space imaging [2], to biomedical imaging [3][4], subsurface prospecting [5], and non-destructive testing and evaluation (*NDT/NDE*) [6].

2. Some Results about the Information Content, the Degrees of Freedom and the Resolution in Linear Inverse Scattering

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Abstract: *In this chapter we present an overview of the general framework we adopt in order to deal with linear inverse scattering problems. Founding on the spectral decomposition of the pertinent operator, we focus on the introduction of the Number of Degrees of Freedom, according to the configuration of the scattering geometrical settings, and on the evaluation of the Point Spread Function, defining the resolution of the inversion algorithm. Since it cannot be always evaluated in closed form, it is discussed how an approximate version can be envisaged and numerically validated. The approach is applied to free-space and half-spaces scattering geometries. In the latter instance a scattered field sampling criterion is derived, too.*

1. Introduction

Inverse scattering problems arise in a very large number of applications, ranging from the nondestructive evaluation (NDE), for the detection of possible crack in civil and industrial structures, in security applications in remote detection of subsurface inclusions, such as unexploded ordnance and mine or for detection of a concealed weapon, in oil industry, for oil and gas exploration, in medicine, for the detection of early stage breast cancer, in subsurface imaging for archaeological purposes or for the detection of buried utilities in urban scenarios.
As it is well known, such problems are extremely difficult to solve due to their non-linearity and ill-posedness. A great deal of research activities has been developed and documented in the literature to address non-linear inverse scattering problems. In this framework, the reconstruction/imaging is usually recast as an optimization problem where the minimum of a suitable cost function accounting for the misfit between the scattered field data and the model data must be found. Newton-like iterative methods are generally the approaches upon which deterministic non-linear inversions are based. As it is well known, such a kind of inversion methods can suffer from convergence problems and can experience limited reliability due to the occurrence of false solutions. These problems stimulated researchers in finding out strategies to overcome/mitigate the drawbacks mentioned above. For example, in order to reduce non-linearity, approximate (quadratic) and novel non-linear scattering models have been developed. Again, in order to exploit in a clever way the ratio between independent data/number of unknowns (which affects the curvature of the functional range and hence the occurrence of local minima) enlarging the number of unknowns as minimization procedure evolves or multi-

3. Microwave Tomography for Unmanned Aerial Vehicle Radar Imaging: State of the Art and Perspectives

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Abstract: *This Chapter deals with microwave tomography as a flexible tool to image surface/subsurface targets from radar data collected by using unmanned aerial vehicles. Specifically, it is shown that microwave tomography allows modelling in a relatively simple way the radar signal propagation in homogenous or inhomogeneous media as well as handling arbitrary measurement modalities and radar antenna configurations. Signal processing strategies capable of accounting for the platform positions as estimated by differential global navigation satellite systems and designed to manage data collected along single or multiple lines are also considered. Experimental examples regarding single track data are presented as a proof of concept assessing the capability to image surface and subsurface targets.*

1. Introduction

Unmanned Aerial Vehicles (UAVs), commonly referred to as drones, constitute an attractive technology in different application contexts due to their autonomous flight capability, reduced mission costs, and the possibility to embark multiple sensors. According to [1], rotary UAVs with a maximum take-off weight smaller than 30 Kg are referred as 'mini UAVs'. The main advantages of mini UAVs are the low cost, ease of use, high flexibility thanks to their vertical take-off and landing capability, and their ability to hover. Conversely, the main disadvantages are the limited endurance (about 20 minutes) and payload mass. Thanks to its advantages, in the last years, UAV technology has experienced a rapid diffusion in several applicative fields such as remote sensing [2], where mini UAVs are often integrated with passive sensors like optical (e.g., visible) or infrared cameras and/or active sensors such as Light Detection And Ranging (LIDAR) and microwave radar.

This Chapter deals with mini UAVs equipped with microwave radar systems, which allow the detection of hidden targets, such as objects buried in the subsoil or inside non-metallic man-made structures, thanks to the ability of microwaves to penetrate visually opaque materials [3], [4]. The combination of mini UAV and radar technology is leading to the conception of innovative imaging systems, which are useful in many fields such as landmine detection [5]-[7], glaciology [8], [9], search and rescue [10], agriculture [11], environmental monitoring [12],

4. The Shifting Zoom as the Way to Make Possible the Application of Inverse Scattering Algorithms to GPR Data

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Abstract: *This chapter deals with the method of the shifting zoom, which allows the effective use of inverse scattering algorithms for the reconstruction of domains much larger than the probing wavelength. Thanks to the shifting zoom, indeed, large amount of data can be managed and accurate reconstruction of electrical large spatial domains can be achieved with an affordable computational burden.*
The method is herein exploited to process GPR data gathered in archaeological sites and to achieve focused images of buried anomalies by means of a regularised linear inversion, performed by means of the truncated SVD of the involved scattering operator. In particular, results relative to experimental data will be shown and compared with a more common migration algorithm, both in a controlled situation and in the field.

1. Introduction

Electromagnetic inverse scattering algorithms constitute a sector of large interest both theoretical and practical, with applications in cultural heritage [1], safety of things and people [2], microwave biomedical diagnostics [3], etc..
It is well known that the problem is ill-posed and nonlinear [4], and several strategies have been introduced to afford it, some of which linear [5-6] and some other nonlinear [7-8]. The different strategies are more or less suitable, depending on the situation at hand and on the kind of targets looked for. In the case of ground penetrating radar (GPR) prospecting, the exigency to consider quite long observation lines (possibly hundreds or thousand times longer than the probing wavelength) has driven to a large use of migration algorithms [9].
The migration is a linear inversion algorithm where the inverse scattering operator is replaced by the adjoint operator. It is a fast algorithm, relatively easy to implement numerically, and it is available in most commercial code for GPR data processing. In particular, it is available in the Reflexw (https://www.sandmeier-geo.de/reflexw.html, last connection on September 29th 2022) and in the GPR-SLICE (https://www.gpr-survey.com/, last connection on September 29th 2022), which probably are the most popular available codes. From a physical point of view, however, beyond the linearization of the inverse scattering operator, a basic migration undertakes further approximations-assumptions, as the hypothesis that the background propagation medium is lossless (the actual losses are heuristically equalized before the migration by means of a gain variable vs. the time depth) and the hypothesis that the targets are

5. Through-the-Wall Microwave Imaging: Forward Modeling and Hybrid Inverse-Scattering Procedures

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Abstract: *In this Chapter, an overview of the results achieved by teams from the CNIT research units of the University of Genoa and University of Roma Tre in the framework of through-the-wall imaging is reported. The through-the-wall imaging problem is dealt with through a comprehensive approach, which considers both the solution of the forward-scattering and the inverse-scattering problems. As forward-scattering technique, the Cylindrical Wave Approach is used. It allows the modeling of the response by targets in a trough-the-wall layout, thus providing synthetic data for the validation of imaging approaches. A hybrid two-step approach relying on an inverse-scattering procedure in variable-exponent Lebesgue spaces is adopted for data inversion. In particular, a preliminary reconstruction, which can be obtained through delay-and-sum or truncated singular value decomposition approaches, is used to build the exponent function used in the second step. The reconstructions on experimental data confirm the robustness of the imaging approach in sensing both high-reflecting and low-reflecting targets.*

1. Introduction

Through-the-Wall imaging (TWI) is a non-destructive technique for the inspection of buildings' interior, aiming at the detection of humans and other targets [1]. The penetration of electromagnetic fields at microwave frequencies through the construction materials of the walls is exploited. The objective is to provide an image of the scene under inspection that may be used in surveillance applications, rescue operations, fire succor, and which is of interest both in the civil and military field. However, the imaging of a target in a through-wall (TW) scenario is a task of higher complexity, compared to the imaging of free space targets or of buried targets [2]. Indeed, in TW propagation, the scattered signal may be strongly affected by attenuation and distortion due to multiple bounces at the wall boundaries, and by absorption due to the construction material. Consequently, ad-hoc solutions, both concerning the measurement hardware and the processing algorithms, need to be devised.
From the point of view of measurement strategies, mainly two architectures can be adopted: Time-domain (using a pulsed signal) or frequency-stepped systems. Both approaches have been considered in the literature. Moreover, monostatic or multistatic setups can be exploited. In both

6. Millimeter Wave Imaging Profilometry for Plasma Diagnostics: Analysis, Design and Preliminary Assessment

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Abstract: *Reliable measurement of the electron density plays a key role in plasma physics. In particular, it is of interest achieving information about local values of electron density in plasma chambers, rather than line-integrated density values currently provided by other diagnostics, i.e., optical emission spectroscopy, X-ray measurements, interferometric and polarimetric techniques. Millimeter wave imaging profilometry (MIP) is an alternative attractive approach to cope with this task, but requires solution of an inverse scattering problem, which, besides being non-linear and ill-posed, shows also severe intrinsic limitations about the kind and class of unknown profiles which can be actually retrieved. In this Chapter, the main results on the use of inverse scattering for MIP are summarized and illustrated, then numerical results are reported to show the feasibility of the proposed approach, with particular interest in plasma diagnostics in electron cyclotron resonance ion source (ECRIS) and possible perspectives in fusion reactors.*

1. Introduction

Plasma physics is one of the most promising theoretical and applied research field ranging from astrophysics to material characterization and nano-electronics, from particle accelerators to nuclear fusion, just to mention a few of them. The measurement of some parameters, such as electron density, plasma temperature and plasma instabilities, plays a fundamental role to understand plasma ignition and combustion. To cope with this task, plasma diagnostics techniques are based on a variety of mechanisms including magnetic measurements, electric probes, refractive index measurements, radiation emission and scattering [1].
Non-invasive electromagnetic diagnostics are based on beam propagation, at microwave (MW) or millimeter wave (MMW) frequencies, which, when propagating through the plasma, are able to actively sense its dielectric properties. Such a kind of active diagnostics comprises three main techniques: interferometry, polarimetry and reflectometry [2]. Interferometry exploits the phase delay of a beam split in two branch lines, one acting as reference path, the other propagating in the plasma chamber, while polarimetry exploits magnetized plasma birefringence, that is the Faraday effect associated to waves propagating along the magneto-static field direction, or the Cotton–Mouton effect, when the wave is propagating perpendicularly to the magneto-static field [2]. Both interferometry and polarimetry allow retrieving the so-called line-integrated value of the refraction index, and are mainly used on large reactors for nuclear fusion, such as

7. Microwave-based Devices for the Quality Assessment of the Industrial Manufacturing of Carasau Bread

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Abstract: *In this chapter we present a summary and overview of the results achieved by the researchers from the University of Cagliari and the Italian Institute of Technology aimed at engineering the industrial production of a traditional food product from Sardinia, i.e., Carasau bread. In detail, to advance, automate and control the industrial production of Carasau bread, the challenge of developing innovative microwave-based devices and technological solutions was faced. A thorough and extensive microwave spectroscopy study was carried out to investigate the complex dielectric permittivity of the food products. Bread dough as a material is heterogeneous and dynamic, while presenting high losses and dielectric strength. With the knowledge retrieved from the measurements, the preliminary design of i) a 3D-printed, wideband double ridge waveguide sensors to measure the dielectric permittivity, and of ii) a moisture patch antenna sensor for the in-line assessment was carried out. The wideband waveguide sensor was designed numerically by shaping the sample holder and its deployment in order to perform transmission measurements. Therefore, the sample inclination, thickness and the size of the sample holder struts were sized, while taking into account the potential manufacturing and prototyping issues. The feasibility of measuring, in a noninvasive and contactless way, the relative percentage of water in a dough sheet was verified. The influence of confounding factors, such as the antenna to the sheet distance and the sheet thickness, on the frequency response of the sensor was studied. This preliminary activities are promising and pave the route to the development of innovative microwave systems for the food industry.*

1. Introduction

Today industry is challenging a drastic transition to a new paradigm, i.e., the so-called Industry 4.0: Digitalization, automation, precision, reduced waste, and high quality products, these are the key words and goals [1]. Food industry is mostly involved in this radical challenge [2]. Indeed, the food industry has special needs and critical aspects. For instance, during the production process, the quality of the food products can change suddenly, thus calling for ad hoc, robust, reliable and real-time strategies to monitor a given manufacturing process. The digital monitoring of the supply chain is fundamental to gain a deep understanding of the main production steps, to identify weaknesses, optimize the process, reducing the maintenance

8. Full Phaseless Approach to Inverse Scattering

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Abstract: *In this chapter, an overview of the research activities conducted at the ERMIAS Lab of the University of Calabria, which are addressed to implement a full phaseless approach for inverse scattering problems, is presented. More specifically, the main focus is achieved by combining two main topics, namely the Inverse Source Problem and the Inverse Scattering Problem. The first topic is faced through the characterization of the electromagnetic source starting from intensity-only field data, by combining a Spatial Domain Indirect Holography Technique (SDIHT) with an incident field calibration method, such as a Modal Expansion (ME) based formulation, or a Source Reconstruction Method (SRM). The second topic is faced through the implementation of a phaseless inverse scattering strategy, based on a Contrast Source (CS) formulation, preliminary applied to canonical objects, considering both in-silico and experimental, data and then extended to the case of heterogeneous targets, with a focus on breast imaging applications. The results reported in this report, summarizing recent published researches by the authors, show that, despite some limitations coming from the phaseless data sparsity and non-linearity, promising imaging results can be obtained when considering even high heterogeneous targets, whereas the inverse source problem enables the use of a phaseless method for the field characterization of radiating sources with different directivity levels.*

1. Introduction

Microwave imaging methods have been an open research field for decades. The applications explored among the scientific community are different, putting a lot of attention and efforts in the development of solution strategies to be applied to a non-exhaustive list of applications, including remote sensing, non-destructive testing, ground penetrating radar, concealed weapon detection and, above all, biomedical imaging. In the latter case, although most of the imaging methods made strides during the years, limited are the case which microwave biomedical imaging apparatus have reached the clinical trial stages. Aside the complexity of the measurement setup, the main challenges in this context lie on the limited predictability of the scattering phenomena in the case of very heterogeneous structure, typically involved in the human tissues. Indeed, despite the existent dielectric diversity among the tissues, a quantitative reconstruction of these properties is definitely the ultimate long-term goal of microwave imaging for biomedical scenarios, with a view to its use as affordable and supportive diagnostic tool. From an analytical perspective, microwave inverse scattering problems are well-known to be ill-posed and ill-conditioned and they face non-linearity issues by nature. Consequently, some strategy needs to be adopted, in order to have reliable and stable solutions.

9. Intracranial Hemorrhage Imaging-based Follow-up: Experimental Assessment Using a Microwave Imaging Scanner

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Abstract: *This chapter presents the experimental assessment of a microwave imaging device for the monitoring of intracranial hemorrhages. The considered low-complexity scanner prototype is made of an array of twenty-two antennas, conformally placed on top the head, a 2-port compact vector network analyzer, and an ad-hoc electromechanical switching matrix. The device exploits a non-iterative linearized differential algorithm together with additional robustizing stages of pre and post data processing that allow performance in real-life conditions. The pre-processing acts directly on measured S-parameters, limiting the effect of noise on the data. Instead, the post-processing compensates the lack of symmetry of the measured scattering matrix to mitigate the artifacts propagated through the imaging kernel. As a whole, the imaging algorithm performs in almost real-time, retrieving instantaneous 3-D qualitative maps of the head indicating the physical temporal variation of the hemorrhage affected area. The proof-of concept experiment consists in monitoring an evolving hemorrhage condition either worsening (increasing) or recovering (decreasing). To this end the hemorrhage is simulated with a balloon gradually filled with blood-mimicked liquid, positioned in an anthropomorphic single-cavity plastic head phantom filled with an alcohol-water-salt mixture resembling the average dielectric properties of the brain. The outcomes show that the system and algorithm are able to indicate and track variations with a centimetric spatial resolution.*

1. Introduction

The intracranial hemorrhage (ICH) is a cerebrovascular life-threatening emergency that involves the rupture of one or more arteries blood feeding the deep inside brain, causing an internal bleeding and, then, blood clot formation and an increase of the brain pressure. The ICH is caused regularly by hypertension, head traumas or arteriovenous malformations, and its treatment consists in stopping the bleeding (hemorrhage) and removing the hematoma to alleviate the brain pressure. The rupture of the arteries thin walls provokes a release of blood

10. Microwave Imaging in Non-Conventional Lebesgue Spaces: Overview and Application to Brain Stroke Imaging

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Abstract: *In this Chapter, an overview of the results achieved by a team from the CNIT research unit of the University of Genoa is reported. It concerns numerical and experimental results obtained by the application of a microwave imaging approach based on inverse scattering for diagnostics of brain stroke. After discretization of the continuous model, the nonlinear equations of the inverse scattering problem are solved by using different versions of a Newton-based method, which has been developed in the framework of non-conventional Lebesgue spaces. A selection of the obtained reconstruction results, with reference to different imaging configurations and working conditions, is reported. Capabilities and limitations of the proposed approaches are discussed.*

1. Introduction

Chapter 9 [2] has been focused on the application of microwaves to stroke detection and monitoring. The present chapter deals again with the same topic and is differentiated mainly by the considered solving approach. The motivations and the importance of searching for new diagnostic tools for addressing this kind of pathology have been deeply discussed in Chapter 10 and will be only briefly recalled here. The focus of the present contribution is to report the achievements obtained by a team belonging to the CNIT unit of the University of Genoa in considering the application of nonlinear inverse scattering methods to solve, in a regularized sense, the equations governing the diagnostic problem.
As it is well known, the inverse scattering problem concerns the reconstruction of a target (in the present case, the "damage" due to stroke) in a given structure (here, the head) starting from measurements of the electromagnetic field performed outside this structure [1]. The structure itself is illuminated by a proper (known) incident radiation (in this case produced by an array of antennas surrounding the head). The starting point for solving any problem involving electromagnetic fields is of course represented by Maxwell's equations, which are coupled vector partial differential equations relating the field vectors and their sources. Polarization,