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Novel Approaches in GPR Data Processing for Health Monitoring of Trees

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Abstract— **The aggressive fungal attack is seriously threatening tree species in forests and woodlands in the UK and beyond. A lot has been said about the spread of disease and fungal attack on ash and oak trees in the United Kingdom and European countries. Within this context, Ground Penetrating Radar (GPR) has emerged as one of the most promising non-destructive testing (NDT) methods for acquisition of information about the internal structure of trees in terms of defect and their root system architecture. Nevertheless, current research has shown that there exists limited information and in depth studies within this important area of endeavour. This review paper reports on the current advances made within the context of GPR applications in health monitoring and assessment of trees and tree roots. This paper also discusses and reports on new areas of development including, the reverse-time migration, the microwave tomography and the pattern-recognition approaches within the signal processing and image analysis (interpretation) contexts.**

Keywords— tree health monitoring, ground penetrating radar (GPR), reverse-time migration, microwave tomography, pattern recognition, tree trunk decay and cavities, tree root mapping

I. INTRODUCTION

Proper maintenance of the ecosystem and conservation of the overall climate conditions are strictly connected with the proper management, health monitoring and protection of forests [1]. To this effect, it is known that the actions of insects and diseases present a serious threat to tree health within European territories [2, 3] and may eventually lead to the complete extinction of certain tree species [4]. Within this context, the current greatest threats are undoubtedly the fungi provoking ash dieback and acute oak decline (AOD) [5], [6].

First signs of the ash dieback disease in Europe date back to 1992, whereas it was first reported in the United Kingdom (UK) in 2012 [7]. Only a few ash species can resist to this disease, and it is predicted that the majority of these trees will die within the next two decades [8]. AOD is similarly very harmful in view of its rapid development within the UK area [6] and the level of aggressiveness that causes tree death within a short time frame, usually a few years [9].

Within this context, an early-stage disease diagnosis is fundamental to identify decayed trees and provide timely remedial actions. A major challenge in this area of endeavour is that early decay can be located in the inner core of the tree without any visible signs of disease on the bark [10]. Tree decay usually develops internally along the stem as hollows or rotten woods and assume a cylindrical shape.

In terms of available assessment methods for decay detection in trees, core-drilling is still the most used. However, the method is fully destructive and can induce further decay around the testing area [11]. To this effect, the use of non-destructive testing (NDT) methods, such as resistograph testing [12], electrical resistivity tomography (ERT) [13], infrared thermography [14], ultrasound tomography [15, 16] and X-ray tomography [17] were reported in this area of endeavour. Within the available electromagnetic (EM) methods, microwave tomography has proven its viability [18]. Use of common offset GPR systems has been successfully proven for large-scale applications in forestry engineering, especially in regard to the monitoring of tree trunks [19]–[21] and root systems [22]–[26] (Fig. 1).

A main constraint in terms of the application of GPR data processing techniques for tree trunk investigations is that traditional processing methods cannot be used due to the cylindrical-like configuration of the trunks and the internal anomalies. Also, it was questionable the full effectiveness of the available GPR processing techniques for the detection of decay in terms of type and location, such as early disease close to the bark, major decay within the tree core areas, bark inclusions etc. To this effect, this paper reports a review on the most recent advances achieved within the context of new data processing approaches in GPR for health monitoring of trees. In particular, the reverse-time (RT) migration approach, the microwave tomography approach and the pattern-recognition approach are discussed. In regard to the use of the RT and the microwave tomography approach in the present work, the case of a set of measurement profiles at a constant height and encircling the sections of the trunk is specifically considered. The pattern-recognition approach is instead discussed within the context of detecting root system architecture.

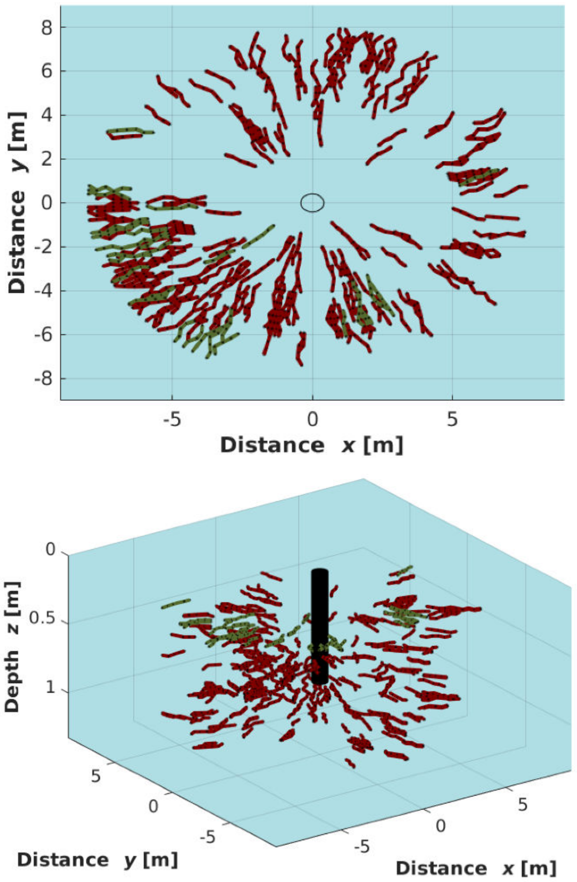

Fig. 1. 2-D planar view (a) and 3-D rendering (b) of the root system architecture invesitgated in [27].

II. THE REVERSE TIME-MIGRATION APPROACH

Reverse-time (RT) migration is based on the exploding reflector model. The latter assumes that subsurface targets can be approximated by equivalent sources that are triggered when reached by the incident field [28]. Consequently, propagating the received fields back in time -using the right electromagnetic velocity model- will force the fields to collapse at the location of potential scatterers [28].

As an example, in the paper proposed by [29], the received fields are propagated back in time using the Finite-Difference Time-Domain (FDTD) method. A 2D configuration has been chosen in order to reduce the computational requirements. The employed spatial step equals with $\Delta x = \Delta y = 2\,mm$ while the time-step was chosen based on the Courant limit [29]. The boundaries of the grid are truncated using the time-synchronised convolutional perfectly matched layer [30] with ten layers thickness. The velocity is assumed to be homogenous within the trunk and is estimated indirectly based on focusing criteria [28]. In particular, a criterion exploiting the entropy of the retrieved image is used in order to choose what is the most focussed reconstructed image on dependence of the dielectric permittivity of the homogeneous background [28]. To compensate the two-way travel time, the simulated velocity should be half the actual one. Therefore, the implemented permittivity has to be four times higher than the estimated bulk permittivity of the trunk [31].

The FDTD grid is excited by multiple sources that are placed at the position of the measurements. The waveforms of the sources are the received signals reversed in time after applying time-zero correction, time-varying gain and a singular value decomposition filter [31]. Notice that the reversed received field should be interpolated in order to be synchronous with the time-step of the employed FDTD [31].

Finally, the migrated image is subject to a post-processing scheme in order to remove migration artefacts and furthermore increase the overall signal-to-clutter ratio. The focussed fields are initially squared and subsequently smoothed using a Gaussian blur filter [31].

RT migration has been successfully validated using both numerical and experimental data (Fig. 2). Artificially created decay of various sizes were successfully detected regardless of their position [31]. Larger decay were more clearly detectable while smaller decay required a more exhaustive pre-processing in order to remove the ringing noise due to the layered nature of the trunk [31].

III. THE MICROWAVE TOMOGRAPY APPROACH

The microwave tomography approach used within the context of tree health monitoring is based on a linearised model of the EM scattering exploiting the Born Approximation (BA) [32]. It is known that BA allows for a quantitative reconstruction of the targets only in the case of anomalies with a weak electromagnetic contrast compared to the host medium. In case the assumption of weak scattering does not hold, an inverse scattering approach based on BA can be still used to detect, locate and gain an estimation of the geometrical shape of the targets [33].

In the research presented in [34] and [35], an inverse scattering approach exploiting a multi-monostatic/multi-frequency configuration (which is the typical configuration for a GPR survey) is adopted. A 2D geometry is considered where the measurement points are located on a domain at a constant height and encircling the slice of the trunk under investigation. The host medium (inside of the trunk) is assumed as homogeneous and characterised by an equivalent dielectric permittivity.

The unknown of the problem is the contrast function accounting for the relative difference in the dielectric properties of the targets [32, 33]. More specifically, solution is given under the form of a spatial map (image) of the contrast function for the inner region of the trunk. Information about the location and the geometry of the targets are retrieved at the areas of the trunk with the highest values of the amplitude of the contrast function.

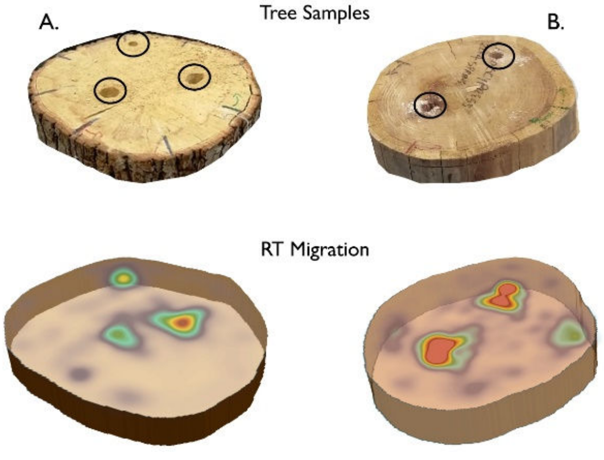

Fig. 2. Two tree samples and their corresponding reconstructed internal structure using reverse-time (RT) migration. The artificially created decay are highligted with circles [31].

In regard to the results presented in [34] and [35], the raw data are collected in the time domain whereas the input data to the inverse scattering approach are given in the frequency domain. To this effect, a pre-processing stage on raw data (in time domain) is required to achieve the input data (in frequency domain) to the inverse scattering approach. The pre-processing accounts for the following steps:

- zero timing;
- time-gating;
- background removal;
- linear gain versus time (depth);
- Fourier transform of the filtered raw data.

The tomographic inversion is performed after the pre-processing stage. More in detail, a Truncated Singular Value Decomposition (TSVD) is applied to make the linear inversion, as a regularisation scheme in order to obtain a robust and physically meaningful solution [32, 33]. Results have proven effective in identifying and locating all the targets. Specifically, it was observed that reflections from targets closer to the bark are stronger than the reflections from targets located more internally in the cross-section [35].

IV. THE PATTERN-RECOGNITION APPROACH

Tree roots in GPR images are usually represented by hyperbolic patterns, comparable to other linear objects such as pipes and cables. Methods for automatic recognition of these mainly linear objects in GPR images can be classified mainly into three types: machine learning based methods, clustering based methods, and Hough transform (HT)-based methods [36]. Machine learning approaches usually require a training process, and the accuracy of recognition results depends on the quality and quantity of the training data [37]-[39], which limits the application. Traditional clustering methods usually require prior knowledge on the number of the clusters, and are not able to detect noisy and interfering hyperbolas. The authors in [40], [41] developed an algorithm named GamRec to handle these problems. However, it was only tested in synthetic radargrams, its application accuracy in practical radargrams is still unknown. Conversely, the HT is a typical algorithm to detect hyperbolic patterns in GPR images. The HT algorithm was first proposed in 1962 by Hough for detecting imperfect curves with certain shapes [42], [43]. It is based on the transformation from a variable-space to the parameter-space. The randomized Hough transform (RHT), as one of the popular variants of the Hough transform [44]-[46], applies random sampling and converging mapping strategy to overcome the drawbacks of Hough transform regarding computational cost, detection accuracy, and resistance to noise [45], [46]. As a result, the RHT has been applied widely in actual automatic recognition of landmines and pipelines in GPR images [47]-[50].

Although the Hough transform class method has been applied successfully for the automatic recognition of objects such as buried pipes and cables in GPR images, few works have been done to evaluate this method in the identification of underground root systems [51]. Thus far, the influence of root system features on the pattern recognition on GPR images remains unclear. Although a single root and a single pipe share similar hyperbolic pattern on GPR image, root systems possess more complex characteristics than underground pipes or cables: (*i*) the size and depth of roots are uncertain; (*ii*) the directions and angles of root stretching are variable; (*iii*) the distribution range of root systems is not certain; and (*iv*) the soil environment where roots grow is more complex. These factors render the automatic identification of root systems more difficult than pipes in GPR images. Nonetheless, the work in [52] applies the RHT for the automatic recognition of root signals in GPR images in both controlled and in situ experiments. The results show acceptable accuracy for most of the datasets with a recognition rate of approximately 80% and a false alarm rate of less than 1.5/m. More recently, the research in [53] represents the first study that combines direct measurements of permittivity and GPR forward modelling techniques. Harvesting and measurement of tree root permittivity is possible, though the process is time-consuming and must be done carefully. The contact between root segment and probe remains a potentially problematic issue, although this can be overcome by collecting a large number of measurements and removing any potential outlier. Future research should focus on including correlations between GPR signals characteristics (e.g. time delays, amplitudes, frequency peaks) and trees and root trees conditions.

V. CONCLUSIONS AND FUTURE PROSPECTS

This paper reports a review on the current advances made within the context of GPR applications in health monitoring and assessment of trees and tree roots. This paper also discusses and reports on new areas of development including, the reverse-time (RT) migration, the microwave tomography and the pattern-recognition approaches within the signal processing and image analysis (interpretation) contexts.

In particular, the RT migration approach and the microwave tomography approach have proven to be viable to detect decay of various size and at different locations within the trunk cross-section. The pattern-recognition approach discussed in this paper is potentially deployable for improving state-of-the-art research within the context of mapping tree root system architecture.

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