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Combined US and UWB-RF imaging of concrete structures for identification and location of embedded materials

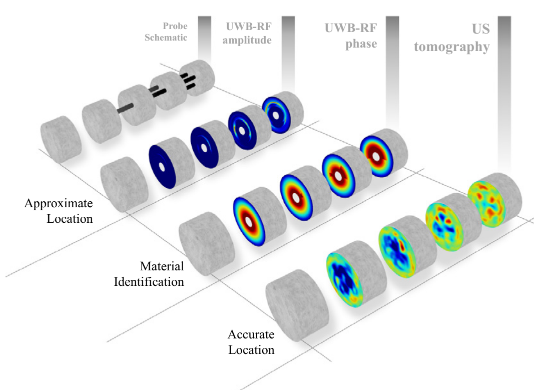
J.L. Blanco-Murillo [a], D. Lluveras [b], V. Yagüe Jiménez [a,b], J.J. Anaya [b], F.J. Casajús-Quirós [a], M.A.G. Izquierdo [a], J.M. Menéndez [a], M.G. Hernández [b,*], A. Herrera [c]

[a] Universidad Politécnica de Madrid, Dept. Signals, Systems and Radiocommunications, ETSI de Telecomunicación, Avda. Complutense 30, 28040 Madrid, Spain
[b] Instituto de Tecnologías Físicas y de la Información Leonardo Torres Quevedo, ITEFI (CSIC), Serrano 144, 28006 Madrid, Spain
[c] Universidad de Cantabria, Dept. of Communications Engineering, Edif. de Ingeniería de Telecomunicación, Plaza de la Ciencia s/n, 39005 Santander, Spain

HIGHLIGHTS

- We report on ultrasonic and ultra-wide band radio-frequency results' fusion.
- Ultrasonic, tomographic images are used to locate bars inside concrete.
- UWB-RF inspections provide further information on the embedded materials.
- Combined analysis allows localization and identification of embedded structures.
- We propose a novel representation, that is easy to follow and interpret.

GRAPHICAL ABSTRACT



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ABSTRACT

We describe how two different techniques: ultrasonic and ultrawide-band radio frequency inspections, can be used and combined to detect embedded structures in concrete. Joint analysis shall overcome limitations of the individual technologies, while providing further information on specimens. In this case, ultrasonic inspection achieves good spatial resolution, while radio-frequency analysis provides information on composition – i.e., material. The proposed techniques were tested on a concrete probe, with embedded reinforcement bars. Images resulting from multisensory fusion provided relevant information regarding the presence, location and material of the bars; and are well suited for in-site inspection, under real ambient conditions.

1. Introduction

Non-destructive inspection of structures has become of great importance in civil engineering. After construction, structures must be monitored to assess their condition, particularly before and after replacing damaged areas. In the event that an intervention is required [1–3], one may like to look beforehand for electric

* Corresponding author.
E-mail addresses: jlblanco@gaps.ssr.upm.es (J.L. Blanco-Murillo), d.lluveras@csic.es (D. Lluveras), virginia@gaps.ssr.upm.es, virginia.yague@csic.es (V. Yagüe Jiménez), jj.anaya@csic.es (J.J. Anaya), javier@gaps.ssr.upm.es (F.J. Casajús-Quirós), miguelangel.garcia.izquierdo@upm.es (M.A.G. Izquierdo), jmm@gatv.ssr.upm.es (J.M. Menéndez), m.g.hernandez@csic.es (M.G. Hernández), amparo@dicom.unican.es (A. Herrera).

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conduits, reinforcing bars, water pipes, water leakages, etc. All relating to materials significantly different from concrete. At this point, one would benefit from every piece of information that can be collected, but damaging must be avoided. Techniques must then rely on the inherent properties of materials to examine the samples. These may vary from one application to another, but all share a similar aim: the localization and identification of these embedded structures.

Among the different techniques that may be considered we focused on the fusion of ultrasonic and electro-magnetic images. Ultrasonic images had been used to characterize the reinforcement in cementitious materials [4], as well as different deterioration processes [5,6] with good results. All these rely on the presence of systematic changes in acoustic impedance, inducing variable attenuations. Nevertheless, it is necessary to further develop the methodologies and inspection systems producing 3D images, aiming for a more comprehensive characterization. Over the last years, several methods and equipment have been applied to provide high-resolution images of concrete areas. Especially for detecting and locating holes, ducts, cracks, and thickness measurements, such as the synthetic aperture focusing technique (SAFT) and tomography techniques [7–9].

More recently, penetration radar was introduced. This is intended for non-destructive diagnosis and testing of structures formed by dielectrics such as those found in wall, roads, dams, bridges, etc. [10–13]. By observing the reflected signals resulting from pulsed, radio-frequency (RF) excitations, one may analyze subsurface structures, focusing on differences among materials regarding electric permittivity. The more advanced systems start to realize how a combination of diverse techniques could be used [14,15].

Alternatively, full transmission assessment has also been addressed for RF inspection. Despite early attempts [16] only marginally have been reported until very recently [17–21]. These still focus on differences in attenuation due to material-specific electric permittivity; just as ultrasonic inspection does for acoustic impedance.

Ultra-wide band (UWB) techniques have been introduced to expand the characterization of traversed materials [22–24]. Instead of individual ones [25], they postulate that differences among materials are better addressed considering wide frequency ranges. Despite similarities with ultrasonic inspection, RF equipment poses specific challenges regarding signal generation and acquisition. These are particularly relevant for UWB applications [26,27], though they are also present in radar (reflection) schemes [28].

A novel aspect to nondestructive testing is the fusion of information from ultrasonic and radio-frequency images. This has been applied to assess concrete properties [29], as well as to reinforced structures [30,31], considering the radar approach; while no contribution has extensively addressed such fusion under full radio-frequency transmission. In this contribution, we describe how US and UWB-RF may be used to provide a combined representation of the inspection results that provides both good spatial resolution and specific information on the composition of the embedded structures. To our knowledge, this is the first attempt to complement US tomographic images with the extended results of RF inspection under ultra-wide band, full response assessment conditions. This joint approach shall prove instrumental, as we believe is the key to develop an integrated methodology for in-site, non-destructive testing of concrete structures.

The remainder of the paper is organized as follows. In Section 2 we describe the proposed two-step procedure for US (Section 2.1) and UWB-RF (Section 2.2) inspection of specimens. We used a cylindrical concrete probe for our tests, which included embedded, reinforcement bars of different lengths. This specimen is described in Section 2.3. In Section 3, we present the results of the inspections and discuss how these can be merged. Finally, in Section 4 we extract some conclusions on the results obtained, and include some future work that should improve upon the results obtained. The work presented here is part of the results of the HORFI project, and was only possible due to the participation of researchers in the fields of ultrasonic inspection, UWB equipment design and manufacturing, RF instrumentation and identification, and construction materials.

2. Methodology

Experimental work covered in this contribution covers tomographic reconstruction based on ultrasonic inspection; and multispectral evaluation of the concrete specimen at different heights. Both techniques are here used considering full transmission, instead of the very common reflected components. A single source is used to excite the US or EM, respectively, while a transducer collects the response induced by changes in the respective field after the excitation traversed the specimen at a given configuration.

The inspection system consists of two other subsystems, (1) the common mechanic inspection, and (2) derivation of parameters' maps, considering at each time ultrasonic and UWB-RF. The first [32] is well-suited for in-site inspection and allows both diametrical and tomographic inspections. The latter are obtained from a coupled roto-translational, rotational movement of its elements: the rotation of the specimen, centred along the axial axis, a vertical movement along the specimen's height and a rotation of the receiving transducer (RX), relative to the transmitter (TX). The coupled movement reduces the number of required transducers, allowing multiple emission/reception configurations in tomographic inspection. Nevertheless, by removing this last relative movement, diametrical inspection is possible. Fig. 1 depicts the systems used for (a) US, tomographic and (b) UWB-RF diametrical inspections.

2.1. Ultrasonic inspections

For US inspection we used the complete tomography system, on immersed specimens and in transmission. This implements the three combined movements described in Fig. 1a. Vertical inspection along height (i.e., z-axis) of the specimen was covered with a 2 mm step. The second movement, referring to the relative position of emitter and receiver, varied a maximum of 220° (±110°), at a 1° step. Thus, it is restricted by 140°. The last movement is the rotation of specimen, being equivalent to a rotation of the emitter. For these we used a 3.6° step, producing up to 100 (360/3.6) records per rotation. In summary, for each revolution of the specimen, the inspection system generates A-scans from 100 emitter positions, times 220 receiver positions (i.e., 22,000 A-scans), resulting in 100 B-scan images, 220 signals each. Diametrical distance between transducers was set to 240 mm.

In Fig. 2a we include representations on energy distribution along time for the sequences recorded from US. B-scan images(s) are obtained out of the 220 signals and describes de amplitude of the received electric pulse collected by the ultrasonic transducer; one per each configuration of the receiver relative to the emitter.

For the emission, amplification, reception and digitalization of the ultrasonic signals, we used proprietary equipment, described in [33]. For the moving emitter and receiver, a pair of Panametrics v413 500-kHz wide-band transducers were used. We generated a 1 μs, 400 V rectangular pulse, and used it as excitation signal at the transducer. At the receiver, we introduced a variable gain amplifier of 20–60 dB, and recorded the resulting ultrasonic response at a 10 MHz sampling frequency.