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RECENT EUROPEAN DEVELOPMENTS IN ACTIVE MICROWAVE IMAGING

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ABSTRACT

At the beginning of the 80's, research programs devoted to short range active microwave imaging have been initiated in Europe. Since that time, a permanent research effort has been organized and oriented toward the development of microwave imaging equipments for industrial and medical applications. This effort has been conducted within the frame of national or european cooperation programs. This paper presents some representative results which have been obtained during the last decade and the general trends concerning their continuation and extension in the next few years. Whithout underestimating theoretical aspects and their importance for further evolutions of microwave imaging techniques, a special emphasis has been given to equipments which provide the real measure of the impact of the recently developed microwave imaging technologies in a growing field of applications.

1 - Microwave imaging specificities

The last ten years have been characterized by the emergence of a new way of approaching, via microwaves, control and imagery problems for ISM (Industrial, Scientific, Medical) applications. By many aspects, this new approach can be considered as relevant to an imaging approach. Until recently, the denomination of microwave imaging was almost exclusively restricted to remote sensing or radar situations, corresponding to long range and, respectively, passive or active imaging modalities. Beside these two important areas which are out of the scope of this paper, microwaves were also used for ISM applications, but without any possible reference to some kind of imaging practice. As a matter of fact, it is worth noting that, during a long time, microwaves have not been really considered as a convenient imaging means for at least two reasons. The first one is that microwaves were not expected to provide adequate image quality. The second and more pragmatic one, consisted in the lack of convenient recording facilities, like films for X-Rays or visible light, for instance. The situation has significantly evolved with respect to these two aspects.

First of all, concerning image quality, only spatial resolution was taken into account, forgetting contrast considerations which have to play a role of at least equal importance. It is true that the propagation of microwaves in inhomogeneous media is relevant to complex phenomena governed by the diffraction rules, resulting in 1) some difficulties to provide well collimated or focussed beams, in 2) limited spatial resolution and in 3) possible image artefacts. In addition, 4) microwaves interactions are very low or negligible with structures or defects which are small compared to the wavelength. But, on the other hand, microwaves interaction with media is primarily sensitive to their dielectric properties (dielectric constant, conductivity) in such a way that microwave images can be expected to provide an indirect access to any physical or chemical factor which these dielectric properties are dependent upon, such as composition, water content, temperature, phase change,... From this contrast aspect, microwaves constitute a very sensitive means to follow up the variations of such factors before, during or after an industrial process or a medical treatment. As for spatial resolution improvement , two ways can be a priori investigated. The first one aims of reproducing optical or quasi-optical situations by increasing the frequency. This way is limited by the fact that, according to a general trend, the transparency of materials decreases when the frequency is increased. For a given material, it is usually considered that the optimum frequency corresponds to the minimum of the loss angle tangent, providing both convenient spatial resolution and penetration. The second way is, renouncing to reduce diffraction effects to an acceptable level, to take them into account as efficiently as possible. Such a way leads to specific wavefront processing (free-space transformation, diffraction tomography,...) which is now beyond the range of performant personal microcomputer. Although less intuitive than a quasi-optical approach, this latter one is probably much more promising.

Coming back to the second explanation of the lesser development of microwave imagery with respect to other imaging techniques, it is evident that the difficulty to record wavefronts, otherwise than mechanically scanning by means of a single probe, had a very dissuasive impact on possible users. Such a probing of microwave wavefronts, over sufficiently large areas, requires too much time and excludes any real-time operation. The evident solution of using probe arrays has, in counterpart, the drawback of cost and/or complexity. Waiting for availability of reliable and cheap Microwave Integrated Circuits, the most reasonable approach, in the present state of the art of microwave technology, would have been to connect a set of probes to the same receiver or at a reduced number of receivers, resulting in microwave multiplexers with unusual high numbers of channels, from a few hundreds to a few thousands. More simple solutions involving only amplitude measurements do not pose such problems but proved to be inadequate in view of possible image improvement via some wavefront processing techniques, which require both amplitude and phase probing. But, some simple techniques (modulated scattering technique, modulated multiplexing technique,...) have been shown to bring convenient technical solutions at supportable cost for ISM applications.

2 - Active microwave imaging in Europe

In the early 80's the scientific european community recognized active microwave imaging as a new area of investigation. The European Microwave Conference awarded its Microwave Prize (Nürnberg, 1983) to this topic [1]. Since that time, a significant research effort has been organized in Europe to promote microwave imaging techniques, both from theoretical and practical points of view. This effort has been conducted within the frame of national or european cooperation programs at three different levels :

- Basic research in reconstruction algorithms
- Development of imaging equipments
- Feasibility studies and evaluation of prototypes in view of diversified applications

Both medical and industrial applications have been considered Some of them are detailed in the two following sub-sections.

a) Biomedical applications

The first researches, undoubtly influenced by the works of Drs. Larsen and Jacobi (Walter Reed Army Institute) [2] have been conducted in the medical domain. More particularly, an important financial support has been provided, in France, by the Agence Nationale de la Valorisation de la Recherche for the non-invasive thermal control of deep hyperthermia. After some preliminary studies [3-5], a few microwave planar cameras, operating at 2.45 GHz, have been fabricated and evaluated for this particular purpose within the french evaluation program TEP[6-7].The key point of this camera consists of its sensor of 32X32=1024 sensitive points, which allows recording wavefronts in amplitude and phase over a surface of approximately 22 cm by 22 cm, at measurement rates variable between 100 and 1000 points per second. Such performances are achieved by means of the modulated scattering technique. Single view focusing and, when possible, multi-view tomographic reconstruction can be achieved, on a personal microcomputer, within a few dozens seconds. In comparison to other imaging techniques (X-Rays, NMR, ultrasounds,...) and as partially confirmed by preliminary evaluations, microwaves offer good thermal sensitivity, inocuity resulting from low irradiation levels, possibility of permanent monitoring, convenient compatibility with heating equipments, moderate cost,... With respect to microwave radiometry, which is the only technique to be clinically used for non-invasive thermal control during hyperthermia sessions, active imaging provides much larger investigation depth and/or sensitivity. As an example, temperature gradients of the order of 1°C are visible over depths extending up to about 20 or 30 cm.

Whereas the previous camera is designed to operate in planar geometry, a circular configuration has been studied at the Polytechnical University of Catalunya (Barcelona), in Spain. This work has been supported by the Health Ministery and has been conducted within a french/spanish cooperation agreement. A laboratory prototype as well as the corresponding reconstruction algorithms have been developped for detecting thermal gradients in the brain [8-11]. The equipment consists of an circular array of 64 antennas operating at 2.45 GHz. When one of these antennas is emitting, the transmitted signal is received by the other ones, and so on. Several experiments realized in the laboratory, on phantoms or volunteers, have confirmed the potentialities of microwave imaging and its actual limitations by the available reconstruction algorithms. Both planar and circular geometries have their own fields of application in which they exhibit comparable and/or complementary performances (thermal sensitivity, point response in homogeneous media,...). In addition, an other structure of equipment has just been studied, consisting of an arrangement of two mutually orthogonal linear arrays [12].

Such a pragmatic and prototype-fabrication oriented approach to biomedical applications has been supported by systematic studies on dielectric tissue characterization under normal and pathological conditions and by theoretical investigations on reconstruction algorithms. For instance, the variations of complex permittivity with temperature have been studied in order to assess the rôle of thermoregulatory processes and, hence, to evaluate the possibility of calibrating microwave images in terms of temperature. Concerning the reconstruction algorithms, a large effort has been devoted to delimit the field of validity of different approximations inherent to the use of the most commonly used spectral approach [13-16]. Today, the results which have been obtained by this technique still remain of limited interest in view of morphological imaging, for which more convenient imaging techniques exist. However, differential imaging appears to be very promising during the follow-up of some parameters changes, during a treatment or due to the natural evolution of a pathology. In the future, this is probably one of the best domain of application of microwave imaging, either for therapy or diagnosis.

Some researches are still continuing in deep or endo-cavitary hyperthermia control, which remains a very motivating challenge, but other possible applications are planned to be investigated in european clinical centers with the existing 2.45 GHz microwave cameras : early detection of fibrosis after accidental or therapeutic irradiation (Institut Curie, Paris), follow-up of rejection after renal transplants (Royal Hallamshire Hospital, Sheffield),... In addition, the algorithm aspect is now seriously reconsidered, particularly in order to take profit from a priori information and to introduce polarization effects. Different optimization techniques seem to be able to remove the limitations of the spectral approach.

b) industrial applications

The techniques developed for medical applications had a very positive impact in the domain of industrial control. It appeared that these techniques could find useful applications to more simple industrial or civil engineering problems as regards to the geometry of the materials, their dielectric properties and the required performances [17]. It is well known that, microwaves are already used for such purposes, but their use is almost restricted to single sensors 1) providing integrated information over a more or less well defined area, or 2) needing to be mechanically scanned in order to obtain data over large surfaces. In the last case, to be obliged to displace the probe constitutes a serious limitation when rapid or real-time operation is needed.

The following examples are representative of a successfull transfer, more or less directly derived from biomedical applications. The first one is devoted to the control of concrete [18]. The problem consists of detecting, localizing metallic bars and, finally, of estimating their diameter. Such a study has been conducted in France with the support of Laboratoire Central des Ponts et Chaussées. It resulted in a portable linear sensor of 64 sensitive points, covering about one frequency octave in the X-band. As compared to other existing techniques (pachometer, gammagraphy), this sensor provides a unique capability to display concrete tomographic cross-sections about 40 cm wide and 10 cm deep. The success of microwave imaging in this application results from the relative simplicity of the structures under test (circular or square barrs) and from the strong contrast between metal bars and the surrounding concrete. More complicated is the case of the detection and identification of buried objects [19]. A compact version for short distance detection, consisting of a 9-11 GHz FMCW radar, has been designed in England, at the Queen Mary College. The radar is controlled by a microcomputer. A number of schemes for signal processing of the radar return have been investigated (FFT, matched filter,...), both theoretically and experimentally. Further work is devoted to achieve cross-polarization measurements. The last example aims to a fine and quantitative diagnostic of dielectric samples. The objective is to derive the absolute complex permittivity from phase tomograms. As expected by using spectral approaches, such an objective can be reached only for low diffracting structures for which Born's approximation is valid. An accurate experimental set-up has been realized at the University of Sheffield, England, and the associated reconstruction algorithms compensate for the particular testing procedure consisting of moving the object under test between two antennas. Experiments on cylindrical shells have demonstrated the limit of applicability of this technique [20-23].

More simple is the following example, consisting of a multi-purpose linear microwave sensor which has been primarily designed for the control of conveyed products [24].The translation of the product or material under test, combined with a rapid transversal multi-point analysis, allows to obtain the microwave image of products moving at speed as fast as a few meters per second. The modulated scattering technique technology provides, at moderate cost, measurement rates of the order of 20 000 to 100 000 points per second. Such a rapidity accomodates the fastest conveying speeds and considerably enlarges the capabilities of usual single point microwave sensors. Such a linear sensor allows to measure the local reflection and/or transmission coefficients of different materials which are assumed to be representative of some property of this material : humidity, local defect, roughness,.... In such a way, it opens the way to real time transverse control over distances extending up to several meters. Evaluations are in progress in various domains of applications : control of paper humidity during drying processes, detection of defects in wooden boards in view of sawing optimization, quality control of laminated/composite layers,... In such applications, the required spatial resolution is of the order of 1 cm. It can be rather easily obtained by means of over -sampling or via wavefront processing, such as free-space retropropagation or synthetic aperture treatment,... Beside these applications, the linear sensor can also be used for the control of more complicated, passive or active, objects, in plane (rectangular, polar) or cylindrical geometries, as it is usual in antenna testing. By the way, it can evidently be used for antenna testing [25-26]. With respect to other non-destructive testing modalities (X-Rays, ultra-sounds,...) microwaves offer some specific advantages for testing microwave materials, that is to say, for materials to be used at microwave frequencies, such as absorbing or transparent materials devoted to radar or radome applications. Indeed, microwave inspection gives access to the final and global quality of the product in terms of absorption or transparency, while other techniques provide information on some partial structural characteristic.

3 - Conclusion

In conclusion, it appears that active microwave imaging is becoming an area of investigation by its own even if it involves more traditional aspects relevant to inverse scattering theory, microwave technology, data and image processing techniques,.... The future of microwave imaging will be strongly influenced by the progresses performed in these domains. But at its present state of development, microwave imaging already offers new possibilities in a wider and wider field of applications, including ISM control or antenna testing and radar imagery. Time is arrived now to learn to see with microwaves, differently than in classical optics and using a specific methodology which is now obtainable thanks to the microwave and computer technology. Even without waiting for expected rapid improvements, the existing equipments already provide the adequate tools to achieve this training to microwave vision.

4 - Short bibliography

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