CONCEPT OF ULTRASONICALLY-BASED MATERIALS CHARACTERIZATION IN NON-CHARACTERIZED ENVIRONMENT

V. Krstelj[1], J. Stepanić[1], and D. Markučič[1]
[1] Department of Quality, Faculty of Mechanical Engineering and Naval Architecture University of Zagreb, Croatia

Abstract: Integration of an ultrasonically-based system for materials characterization and a hand-probe was demonstrated to have a large potential in detection of buried mines for the purpose of humanitarian demining. In the integration, the absence of interferences with the conventional, contact technique of hand-probe use was emphasized. The characteristics of buried mines severely restrict hand-probe manoeuvrability and rate of additional information collectable within reasonable time, thereby lowering quality of the hand-probe-buried object contact. Additionally, the hand-probe penetration through the soil imposes restrictions on the applicable designs of hand-probe tip. All these restrictions influence the characteristics of the piezoelectric sensing part, which must on the one hand provide the operator with a signal of signal-noise ratio sufficiently high to make possible extraction of a statistically significant quantity of information about the buried object material, and on the other hand be as robust as possible, i.e., utilizable in a rather broad palette of mine-soil systems.

In the paper we formulate the model of ultrasonic propagation in the system consisting of a piezoelectric element, hand-probe tip of variable geometry, realistic models of buried objects and characteristics of the non-homogeneous soil region in the close vicinity of the contact of hand-probe with the buried object.

Capability of the presented concept in detecting buried mines is estimated, preliminary theoretical and experimental results discussed, and future development projected.

Introduction: The implementation of specially developed techniques is for some time seen as the only possible way to improve the technical part of humanitarian demining, especially the antipersonnel mine detection (APMD) phase [1 – 3]. The techniques developed utilize on the one hand robust, well-developed and easily-adaptable mechanical and electronic equipment for application in humanitarian demining that is on the other hand suppressed by the experience gathered from the field work [4].

Currently, humanitarian demining at a given area is performed using several demining techniques [1, 2, 5]. Owing to the requirement of sufficient probability of detection, in all of these the manual demining is included [6]. That is a regular situation encountered independently of the techniques used before the last in the sequence, the manual demining technique. One of the consequences is that the improvement of technical characteristics of the manual demining is the crucial task for obtaining improved, thus safer and faster, humanitarian demining.

In this paper we concentrate on the research in improvement of the manual demining with hand probes [6 - 11]. Hand probes are connected with the riskiest in operation, yet most reliable demining technique. They enable the deminer to find about the existence of some buried object, and not more. As practice has shown, that is rather insufficient information having in mind the fact that the antipersonnel mines are rather rare objects in comparison with diverse objects found in the soil. Therefore discriminating capability of hand probes is primarily too high false call rate. The improvement of signal recognition would make a significant contribution in the reliability of results. Since nowadays humanitarian demining is relying on the probing technique that could have a significant impact on the whole process of demining.

Presently, hand probes differ in subsidiary characteristics, like are their shape, material from which they are built, etc. However, there are few researches with emphasis on the hand probe demining capability, in particular its discriminating, or in other words confirmation capability.

Recently, these problems were systematically presented and the context of their resolving was formulated as the OCULAR technique [1, 12 – 14]. Regarding the hand probe improvement, two substantial directions of improvement were extracted, Fig. 1. One direction optimizes the local richness of information, i.e., the quantity of information about the buried object. It is realized as the integration of ultrasonically based sensor for buried object materials characterization with the appropriately designed hand probe. The other direction optimizes global richness of information, i.e., contributes to sharing of information about the soil, its content and other relevant pieces of information collected during demining-team work in a given area. It is realized as the integration of the hand probe wirelessly with the real-time process center, the expert system.

The added value of the directions is clearly seen from the comparison of the working practice (A) and assumed practice realized after the directions described are implemented: A) during demining team work, each deminer obtains some information regarding the soil, distribution of buried object types and positions, which are important in classification of further objects found. If there is no information sharing between a deminer and the rest of the team, then each deminer would obtain total quantity of information available from the terrain only after complete terrain is demined. That is, however, impossible, as each deminer covers only a portion of a terrain. B) each deminer collects a portion of information which is transferred to the central unit, the expert system which both evaluates constantly all the pieces of information presently collected and transfers perpetually these pieces to all deminers. In that case each deminer obtains the maximal available quantity of information regarding the demined terrain rather fast. Overall, in case B the underlying classification of newly encountered buried objects is performed using on average much larger quantity of information.

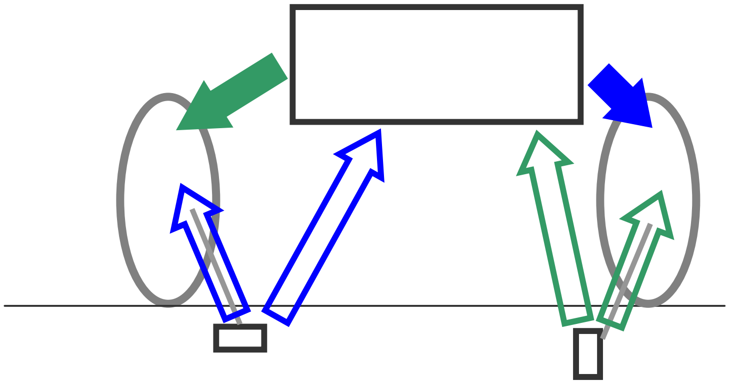

Fig. 1. Local information extraction (empty arrows) and global information sharing (filled arrows) during demining using hand probe. Ovals represent deminers or automatic demining equipment, while the box represents central unit, the expert system.

In this paper we concentrate on the improvement of local information extraction, i.e., the hand probe's tip as it should both enable the deminer to apply low-fluctuation force to penetrate the hand probe and to make possible significant transmission of ultrasonic impulse between the hand probe and the buried object surface. In one of the recent Fast Probe's formulation the materials acoustic characterization is based on acoustic impedance matching. In more detail, ultrasonic impulse emitted from the transducer, mounted near the probe's tip, is scattered at the interface between the probe and the buried object. Reflected part of the scattered impulse is registered by the transducer and subsequently analyzed. In case of matched impedances, the transmission is maximal, i.e. the reflection is minimal. Hence, buried object surface material is recognized as the material causing minimal reflection of the ultrasonic impulse, in case of constant or controlled other parameters in the model. When buried object surface is made of polymer, which in most cases means low metal content antipersonnel mine acoustic impedances are matched. Regarding acoustic impedance matching, it has been confirmed that the approach is fruitful in controlled laboratory conditions, in reduced geometry. Furthermore, in aligning the exploited conditions with realistic ones, the influence of non-characterized contact layer, made of local soil and formed between the probe's tip and buried object surface, was analyzed. It was shown how to include the homogeneous contact layer influence into the materials characterization results.

In the second section the underlying model is briefly sketched. Results of the model are presented and discussed in the third section. Conclusions and lines of future development are given in the fourth section.

Model: The model describes the propagation of the ultrasonic wave through the complex geometry of the hand probe's tip, contact layer formed from the neighboring soil and surface region of the buried object with which the hand probe is in contact. In the first phase the one-dimensional propagation of the ultrasound is analyzed. In the second phase, the geometrical effects are explicitly taken into consideration.

In the first phase one-dimensional model of the linear approach to plane ultrasonic wave incidence is considered [14, 15]. Information about buried object is the acoustic impedance of its material. The acoustic impedance influences transmission coefficient. The linearity makes possible determination of frequency dependent transmission coefficient, further facilitating treating the ultrasonic sensor spectrum as a partially variable quantity. Reduction of, generally, three-dimensional spatial propagation problem onto the problem of one-dimensional propagation is possible because of the following two characteristics of piezoelectric specimens used: (i) in order to minimize the influence of boundary conditions higher frequencies are favored, hence thinner piezoelectric specimens used; (ii) the signal to noise ratio is enhanced using, as a relatively simple measure, the specimens of relatively large diameters as these emit ultrasonic waves of relatively large energies. Overall, the ratio of the specimen diameter to thickness is larger than three, allowing as the initial analysis the aforementioned one-dimensional approach.

In the first phase the goal is to differentiate the structure of the probe's tip surrounding, i.e., to differentiate between the un-characterized soil contact layer and buried object material. That is rather efficiently accomplished as the contact layer functions as rather thin coating of the buried object, which does not significantly screen its acoustic impedance.

In the corresponding experiment the ultrasonic probes in contact (using water or lubricant) with tested specimen (polymer, stone and steel), are connected to ultrasonic devices. The ultrasonic devices generated ultrasonic impulses to the probes, and recorded reflected parts. Stored A-scans were transferred into PC and were processed afterwards. Details on the equipment are given elsewhere.

Reflected part of interest originates in the modification of the initial voltage pulse which is incident in the probe. The reflected part of initial ultrasonic impulse is a complex combination of reflections caused within the probe and reflections from the interface of probe with surrounding medium, in particular the contact layer and, because of the relatively thin contact layer, the specimen material. Overall, different specimen materials modify ultrasonic impulse differently, bringing about different A-scans, as sketched in Figure 2, the difference being characterised using the signal processing algorithm. Full (dashed) line represents case of probe in contact with air (some object). Green (blue) refers to part of impulse originating within the probe (probe-surrounding media boundary). Red arrows represent changes in heights of two peaks within impulse, V_1 and V_2, two of the parameters that are used in order to quantify the difference in response of different materials. Along with that height, the difference in heights of other peaks, or some geometrically more complex derivates of the impulse shape, are in general used in signal processing. One is here, therefore, working in a non-standard operating mode of ultrasonic testing system, considering the fact that it is regularly operated in such a way that information is contained in the impulses recorded after initial impulse ceases.

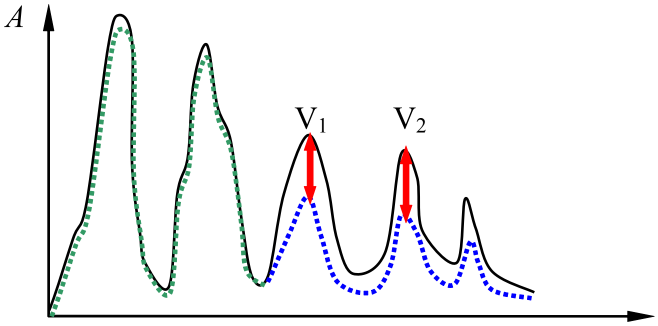

Figure 2. The local maxima of ultrasonic impulse which are used in two-parameter differentiation of the buried objects.

By linearly transforming plane V_1V_2 the clearer differentiation of the groups belonging to different specimen materials is possible. Systematic approach for that is application of the *discriminant analysis*. The results are shown in Fig. 3. The results are obtained after recorded pairs of peak heights are treated using discriminant analysis incorporated in software *Statgraphics 5.0*. Geometrically, discriminant analysis corresponds to a rotation of the axes abscissa and ordinate of the initial rectangular co-ordinate system, with additional scaling (Fig. 4). The rotated variables, denoted f_1 and f_2, are the linear combinations of the recorded peak heights.

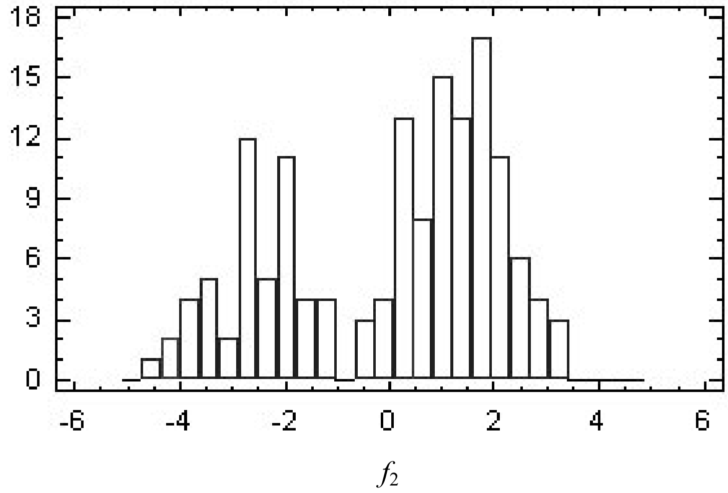

Figure 3. Statistical frequency of different combinations of the values of function f_2, which is the linear combination of the recorded ultrasonic impulse's peaks, as shown in Fig. 2.

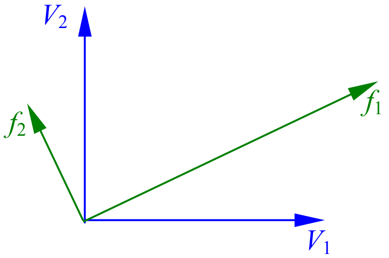

Fig. 4. Sketch of the transformation $(V_1, V_2) \rightarrow (f_1, f_2)$.

The histogram shown in Fig. 3 corresponds to 147 measurements. The particularly important characteristic of the histogram in case of measurements of the ultrasonic reflection with two materials representing materials of buried objects is that two different materials have records which are clearly separated (the separation line being shown as the red dot-dashed line). The similar result is obtained in case of more than two different materials, however then the visualisation of the results becomes problematic and requires considerably larger effort.

In the second phase the realistic geometry is explicitly considered. Several requirements of the model are important for its foundation. First, the previously motivated maximization of the piezoelectric specimen diameter means that significant part of the ultrasonic impulse is scattered from the tip boundary. That could be prevented with the more complex probe design, yet the suitability of the probe to terrain conditions forces the realization of the equipment to be as simple and robust as possible. Because of the diverse factors, the different amount of signal belonging to the scattered ultrasonic impulse in the recorded signal converges toward the design of the ultrasonic impulse using, as the variables, the geometrical characteristics of the conducting electrodes, used to excite the piezoelectric specimen. Sketch of the parameters of the electrode on the side of the specimen nearer to the probe's tip is shown in Fig. 5. In general, number of belts is variable, and not necessarily restricted to two, as shown in Fig. 5.

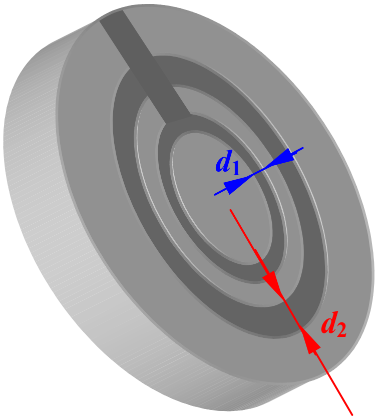

Fig. 5. Sketch of the geometry of one side of the piezoelectric specimen with electrodes realized as mutually connected circular belts of different inner radii and thicknesses (d_1 and d_2).

The description of ultrasonic impulse distribution, as generated by the vibrating specimen of the kind sketched in Fig. 5 requires complex modeling, the complexity introduced by simultaneous treatment of the following factors:

- finite propagation time of the wave traveling through piezoelectric specimen, thus time-distributed phase differences of the surface points,
- reaction of the surrounding (heterogeneous slabs figuring as the acoustic impedance matching objects), which depends on the choice of its materials,
- electro mechanic character of the piezoelectric waves,
- diverse technologically induced effects

Results: Specimens of PZT were obtained and modified (Fig. 6) in order to check in practice the near-field ultrasonic impulse's pressure distribution. Originally both sides were completely covered with the silver electrodes. One side was ground until the silver was removed. After that the new silver electrode was formed using *Physical vapor deposition* technique [16]. In the work conducted, the electrode forms circle concentric with specimen cross-section. The diameter of the circle is variable. The thickness of the electrode is additional parameter, or (in the more general case) the unknown function. For the specimens modified it was taken to be a constant, several orders of magnitude smaller than specimen thickness.

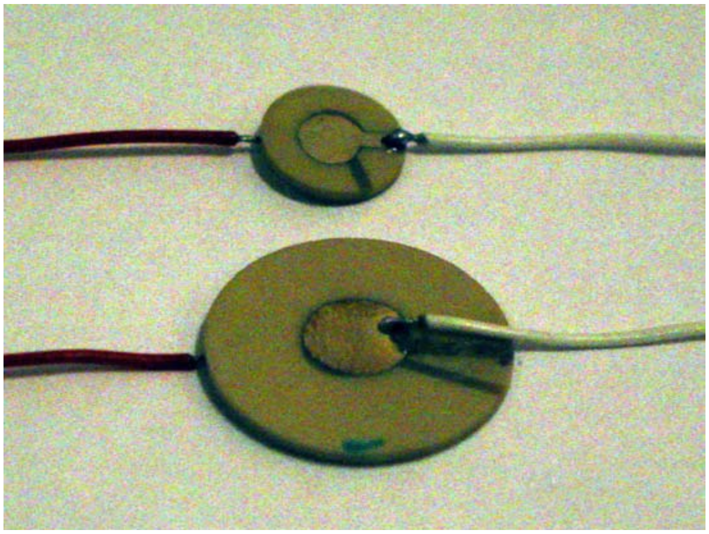

Fig. 6. Two examples of the specimens modified.

If the emitting part were similar to the axially vibrating piston, in that particular case the pressure distribution would have broader angular emission pattern. However, the complex electromechanical piezoelectric wave propagation that occurs makes the direct measurement of the pressure distribution simpler than modeling.

The surface profile of the modified side, obtained using Mahr Perthometer S8P, on some diameter path is shown for one specimen in Fig. 7.

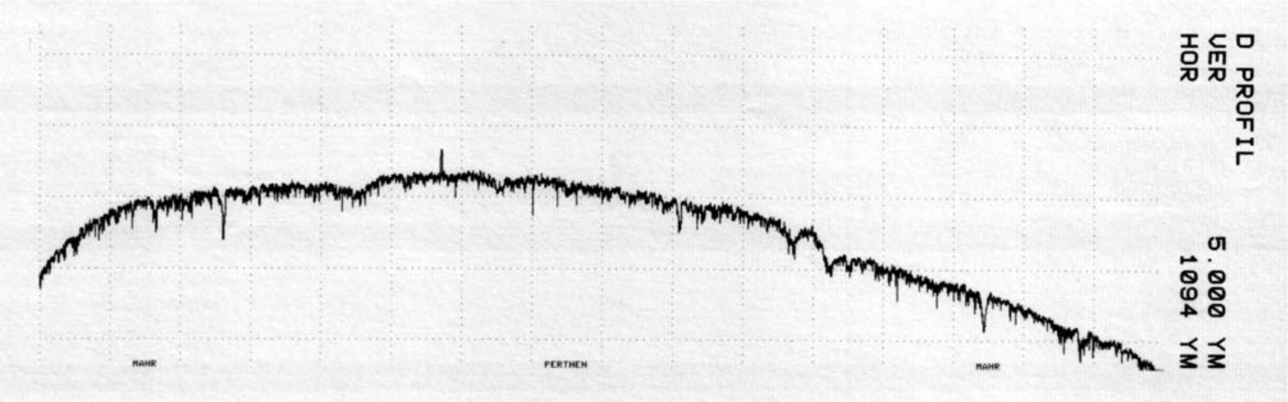

Fig. 7. Surface profile of the modified side of the two of specimens shown in Fig. 6.
Arrows point to the boundary of the deposited electrode.

Conclusions: The manual demining is unavoidable part of the humanitarian demining, as observed in all practical realizations, which is responsible for the most of the total duration and risk of the humanitarian demining. It is, therefore, the primary target of the efficient improvement of the technical part of the humanitarian demining.

The improvement is operationalized as two-phase process, incorporating both the local modification of the hand probe and global formulation of the wirelessly connected system of deminers in a working field and central, real-time processing unit. In this paper the modification of the hand probe, in particular through incorporation of the ultrasonic sensing unit near the probe tip, is presented. The conducted part of the on-going research is described. It consists of preparation of the suitably modified piezoelectric specimens. The modified part is shape of the electrode on the one side, as it makes possible to take into account – and suitably utilize – the scattering of the emitted ultrasonic pulse on the boundary of the hand probe tip between the piezoelectric specimen and the probe end.

Projections of the future work is the following list the combination of which elements is to be investigated:

- the surface and volume parameters of the electrode geometry,
- the precise form of the curved shape of the probe tip and
- of the materials selected

Acknowledgments: The authors acknowledge help provided by I. Krstelj who developed the described expert system application. D. Korošak and Ž. Grgec kindly performed the designed specimens' modifications, and S. Mahović kindly measured the surface profile.

Authors acknowledge the support of the Croatian Ministry of Science and Technology, realized through the projects MZT 0120 046 and 0120 098.

References:

1. Krstelj, V.; Stepanić Jr. J.: Humanitarian de-mining detection equipment and working group for antipersonnel landmines detection, Insight 42(3), pp. 187-190, 2000,
2. Bruschini, C.; Gros, B.: A Survey of Current Sensor Technology Research for the Detection of Landmines, Int. Workshop SusDem '97, Zagreb, Proceedings, pp. S6.18-S6.27, 1997,
3. various authors: Mine Identification Novelties Euroconference '99, Milano, Proceedings, 1999, see also: http://demining.jrc.it/aris/events/mine99,
4. UN Mine Clearance Policy Unit, International Standards for Humanitarian Mine Clearance Operations, see also: http://www.mineclearancestandards.org,
5. Kingsbury N.: Land Mine Detection DOD's Research Program Needs a Comprehensive Evaluation Strategy, US GAO Report, GAO-01 239, 2001,
6. Stepanić Jr., J.: Material Characterization by Mechanical Point Contact Impact Emitted Ultrasound, 15th WCNDT, Rome, Italy, Proceedings, 2000, see also http://www.ndt.net/article/wcndt00/papers/idn074/idn074.htm,
7. Trevelyan, J.: http://www.mech.uwa.edu.au/jpt/Default.html,
8. Humanitarian Demining Technology Development Programme: http://www.eng.warwick.ac.uk/DTU/mines/
9. Antonić, D.; Ratković, I.: Ground probing sensor for automated mine detection, KoREMA '96 – 41st Annual Conference, Opatija, Croatia, 1996., Proceedings, pp. 137-140,
10. Horowitz, P.: http://seti.harvard.edu/mines/jason.htm,
11. Borza, M. A.; De Witt, F. G.: Acoustic landmine prodding instrument with force feedback, US Patent #6 109 112, 2000,
12. J. Stepanić, *Design of Resolving Power of Buried Objects Materials Characterisation Sensor*, 8th ECNDT, Barcelona, 17.-21. June 2002, Proceedings - CD ROM, 2002,
13. V.Krstelj, *Buried landmines detector using ultrasonic materials characterization*, WIPO Patent Application, No. 03/008895,
14. J. Stepanić, H. Wüstenberg, V. Krstelj, H. Mrasek: *Contribution to classification of buried objects based on acoustic impedance matching*, Ultrasonics **41**, pp. 115-123, 2003,
15. Rose J. H.: Ultrasonic Waves in Solid Media, Cambridge University Press, New York, 1999, Ch. 4.,
16. J. Stepanić, D. Korošak, B. Cvikl, D. Markučič, *Piezoelectrically-based Sensing Configuration Optimised for Restricted Characterisation of Materials*, MIDEM 2003, Ptuj – Slovenija, Proceedings, pp. 143-148.