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Water supply system component evaluation from GPR radargrams using a multi-agent approach☆

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Abstract

This paper uses a multi-agent approach as a quick and easy tool for the interpretation and analysis of the characteristics of Water Supply System (WSS) components when working on a collection of Ground Penetrating Radar (GPR) survey files. The multi-agent algorithm proposed in this paper has been developed in Matlab and is based on Game Theory. The input is the result of the GPR radargram survey and the output consists of the agent scores in the game proposed in this paper. Useful information can be gained by interpreting the columns of the output matrix that describe the agents' movements, together with the associated racing times. In effect, this analysis enables a simple determination of the electromagnetic properties of the underground system and provides an accurate classification of these properties. The results of this agent racing algorithm are promising, since it groups, and consequently, decreases the number of points that make up the initial radargrams; while at the same time preserving its main properties, and enabling clearer views of pipes and a better identification of the components in WSS.

Keywords: ground penetrating radar, signal processing, images processing and analysis, multi-agent systems, agent race.

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1. Introduction

Ground penetrating radar (GPR) has been extensively used as a non-destructive methodology to analyze components and anomalies in water supply systems (WSS). The components most frequently analyzed are pipes; while only a few incipient attempts have been made regarding leaks. Information about components, changes undergone, and anomalies is necessary for the productive control and management of a WSS [1]. The following information is crucial for achieving the goals of WSS technical management: identification of illegal connections, planning of supply systems, simulation and operation of networks, correct operation of plumbing systems, maintenance, rehabilitation and renewal of components, detection and control of leaks, application of Graphical Information Systems (GIS), and evolution of pollutants in the networks, among others. Recent studies, such as those performed by the US Environmental Protection Agency (USEPA), underline the use of non-destructive tools such as methodologies favoring technical management of WSS - instead of destructive testing tools [2]. However, even though information retrieval by non-destructive methods is worthwhile, interpreting the huge volume of generated information usually requires high levels of skill and experience.

Many GPR-based works have been developed that attempt to locate and detect components and anomalies in WSS. For example, some works apply methodologies borrowed from other non-destructive methods such as background removal and migration [3], and other works aim to clean images of metallic pipes taken in GPR surveys. In addition, works related to leakage make use of Hilbert and Fourier transforms [4]. The Hough transform has also been used in pattern, mainly hyperbolae, identification [5], and for segmenting and cleaning buried pipes [6], and in works devoted to optimal visualization of buried pipes [7]. Other works have focused on intelligent systems to automatically detect pipes in GPR images. Among these, it is worthwhile quoting: the use of neural networks [8], studies based on support vector machines [9], the application of fuzzy logic for the identification of patterns in the processing of GPR images [10, 11], or the location of plastic pipes using multi-agent techniques [12]. The success of these methodologies hinges mainly on the cleanliness of the images obtained when using classification pre-processing. In most cases, the objective is the identification of the typical hyperbolae that identify the objects of interest in the image under study.

The multi-agent paradigm is used in this paper to evaluate components of WSS from GPR radargrams. The aim of this work is to provide non-highly qualified technicians with non-destructive, easy, and computationally efficient procedures for interpreting GPR survey files. These procedures enable technicians to gain insight into the layouts of the systems, and uncover various concealed characteristics of WSS components. Following the same line of research on GPR image processing discussed in a previous work by the authors [7], this paper takes the matter further by presenting a new multi-agent algorithm.

The remainder of this paper is organized as follow. In the first section, a brief introduction to the work and GPR methodology is presented. The following section introduces and develops the principles for the proposed multi-agent methodology. An experimental case in which the proposed methodology has been applied is shown in Section 3. A conclusions section closes the paper.

2. Proposed method

In this section, we explain the principles of 'racing' as a multi-agent activity and describe aspects of multi-agent behavior programming. Agent racing provides an interpretation and a grouping method for data from GPR radargrams.

A multi-agent system consists of a population of autonomous entities (agents) situated in a shared structured framework (environment) [13]. Significant contributions of multi-agent systems to WSS may be found in the works of Gianetti et al. [14] and Izquierdo et al. [15, 16]. In a system representing some reality (a radargram in our case) agents may be either exogenous or internal factors in the system. The multi-agent system is based on such tools as game theory and the agents are disseminated within the system to assess their immediate environments and make decisions about themselves, or their neighboring agents, or their environment. It is a system composed of subsystems at arbitrary nesting depths and different levels of abstraction. Given a fixed level, the individual components will be the agents that decompose the whole system into different parts, and these are examined in a decentralised manner. This is more often efficient than working directly in some global approach. Agents operate independently (in our case) but they can also interact with their environment and coordinate with other agents [17].

The *agent racing* algorithm we propose has been developed in MatLab and is based on game theory. Game theory uses models to study formalized interactions between incentive structures (games) and carry out the decision process. Thus, the optimal strategies, and the expected and observed behavior for the agents (players) are studied. For a game to be in normal form [18] (such as the game we propose), the following requirements must be fulfilled:

1. There is a finite set P of agents, which we label $\{1, 2, \ldots, n\}$.
2. Each agent s in P has a finite number of strategies, making up a strategy profile set, Σ.
3. A *payoff function* is a function $F : \Sigma \to \mathbb{R}$, whose intended interpretation is the award given to a single agent at the outcome of the game.

Accordingly, to completely specify a game, the payoff function has to be specified for each player in the agent set $P = \{1, 2, \ldots, n\}$. So, the game is a function $\pi : \prod_{s \in P} \Sigma^s \to \mathbb{R}^n$, [19]. Following the description of agent racing principles, we describe the proposed algorithm.

The input of the agent racing algorithm is the radargram, which is the result of the GPR survey, a matrix of size $m \times n$. The dimension m is the volume of signal data each trace records, which depends on the characteristics of the equipment used. The sample is an equipment parameter, commercial equipment being general sets of 512, 1024, and 2048 samples/trace. The n traces generated by the GPR survey are used as pseudo-parallel tracks for the n agents to compete. During the race, each agent s in P builds its vector of strategies k_s, whose $i-th$ coordinate is the strategy taken by the agent at time i. To build these successive strategies the agent examines its associated column, its track, which we call b, in the prospection matrix, as explained in the following paragraphs. The agents' competition evolves in time from $i = 1$ until $i = m$. In the competition each agent s in P has four properties: a) interpretation, b) decision to move, c) movement time, and d) the race phases.

2.1. Interpretation

For each time during the race, an agent takes one value of the trace (b_i); and then this value is compared with two more signal values, the before-value b_{i-1} and the next-value b_{i+1}; and a binary value is generated as a result.

$$bin_i = \begin{cases} 1, & \text{if} \quad i = 1 \\ 1, & \text{if} \quad b_{i-1} < b_i < b_{i+1} \vee b_{i-1} > b_i > b_{i+1} \\ 0, & \text{if} \quad b_{i-1} > b_i < b_{i+1} \vee b_{i-1} < b_i > b_{i+1} \\ 0, & \text{if} \quad i = m \end{cases} \tag{1}$$

2.1.1. Interpretation exceptions

The exceptions for the interpretation property are related to the equalities between the current value and the contrast values (before and next values). Thus, one or both contrast values can equal the value of the current time. The equalities can be due to causes such as: a) wave amplitude values being too small to be differentiated among themselves; b) application of filters; c) failure to emit antenna signal because of internal faults; d) highly reflective soils; and e) others.

The agent will look back and forward in search of times, for which the contrast values (before and next, respectively) are different to the current time value. These searches enable an agent to interpret the $bin = 0$ position. This value is compared with the current position and as a result the binary value for the current position is generated. The exception interpretation pseudo-code is shown in Table 1.

Table 1: Looking for the $bin = 0$ position. Interpretation exceptions pseudo-code.

...*looking back*
i1=1
while ($b_{i-i1} = b_i \vee i1 \leq i - 2$); do $i1 = i1 + 1$; end
...*looking forward*
i2=1
while ($b_i = b_{i+i2} \vee i2 \leq m - i - 1$); do $i2 = i2 + 1$; end
...*searching the* $bin_{i3} = 0$ *position*
$i3 = round\left(\left(2 \cdot i - i1 + i2\right)/2\right)$

where $i1$: is the number of before times the agent looks back to get a value different from the value for the current time. $i2$ is the number of next times the agent looks forward to obtain a value different from the value for the current time. $i3$ is the time when the agent assumed that the binary value is zero.

After time $i3$ obtained, the interpretation rule for exceptions is determined by Equation 2.

$$bin_i = \begin{cases} 0, & \text{if} \quad i3 = i \\ 1, & \quad otherwise \end{cases} \tag{2}$$

2.2. Decision to move

An agent's decision to move is based on the binary value variation. According to this variation, a property called stamina varies positively (variable $StaIni$, Equation 3) or negatively (variable $StaEnd$, Equation 4).

$$StaIni = \begin{cases} 1, & \text{if} \quad i = 1 \\ StaIni + 1, & \text{if} \quad bin_{i-1} = 0 \wedge bin_i = 1 \\ StaIni, & \quad otherwise \end{cases} \tag{3}$$

$$StaEnd = \begin{cases} 0, & \text{if} \quad i = 1 \\ StaEnd + 1, & \text{if} \quad bin_{i-1} = 1 \wedge bin_i = 0 \\ StaEnd, & \quad otherwise \end{cases} \tag{4}$$

When the total stamina is zero, that is $StaIni$ equals $StaEnd$, the agent receives its payoff for the effort performed. This is accomplished by the variable $AgeMov$. As explained in subsection 2.4, this is applied during the 'official' race, just after the *warming-up*.

$$AgeMov = \begin{cases} 0, & \text{if} \quad i = 1 \\ AgeMov + 1, & \text{if} \quad StaIni = StaEnd \wedge t_w \neq 0 \\ AgeMov, & \quad otherwise \end{cases} \tag{5}$$

2.3. Movement time

Each effort developed by an agent happens between a start time and end time. These values, associated with the agent movement ($AgeMov$) are stored in two agent personal vectors, namely, $StaTiIni$ (Equation 6) and $StaTiEnd$ (Equation 7), respectively.

$$StaTiIni_{AgeMov+1} = \begin{cases} 1, & \text{if} \quad i = 1 \\ i, & \text{if} \quad bin_{i-1} = 0 \wedge bin_i = 1 \end{cases} \tag{6}$$

$$StaTiEnd_{AgeMov} = \begin{cases} 1, & \text{if} \quad i = 1 \\ i, & \text{if} \quad bin_{i-1} = 1 \wedge bin_i = 0 \end{cases} \tag{7}$$

Moreover, every agent movement ($AgeMov$) has one associated $MovTi$ movement time that we define as the average time between the stamina's time start ($StaTiIni$), and the stamina's time end ($StaTiEnd$). A component of $MovTi$ is defined every time the difference between these stamina values is 0:

$$MovTi_{AgeMov} = \frac{StaTiIni_{AgeMov} + StaTiEnd_{AgeMov}}{2} \tag{8}$$

2.4. The race phases

The race comprises two phases: a) *warming-up*, and b) *racing*. The phases are characterized by two times: a warming-up time (t_w, Equation 11), and a racing time (t_r), totaling a time $t = t_w + t_r$, where the t_w time corresponds to the time for the agent to overcome the end wave amplitude value ($AmplEnd$, Equation 9) in some percentage of the average wave amplitude value for the before-values for the current time ($AmplProm$, Equation 10).

$$AmplEnd = \begin{cases} 1, & \text{if} \quad i = 1 \\ b_i, & \text{if} \quad StaIni = StaEnd \\ AmplEnd, & otherwise \end{cases} \tag{9}$$

$$AmplProm = \begin{cases} b_i, & \text{if} \quad i = 1 \\ \displaystyle\sum_{j=1}^{i-1} \frac{b_j}{(i-1)}, & otherwise \end{cases} \tag{10}$$

$$t_w = \begin{cases} 0, & \text{if} \quad i = 1 \\ MovTi_{AgeMov}, & \text{if} \quad |AmplEnd| > x \cdot |AmplProm| \wedge t_w = 0 \\ 0, & otherwise \\ t_w, & \text{if} \quad t_w \neq 0 \end{cases} \tag{11}$$

where $x = 1.1$, this being an experimental value.

2.5. Recommendations

In the proposed method (Section 2) the raw traces can be used. However, we recommend data interpolations so that the use of interpretation exceptions (subsection 2.1.1) is minimized. Among the interpolations most used in GPR to correct and find the truth peaks - the linear, polynomial, and cubic spline [20, 21] must be quoted. In this work, we use the cubic spline interpolation. An example for a trace is shown in Figure 1.

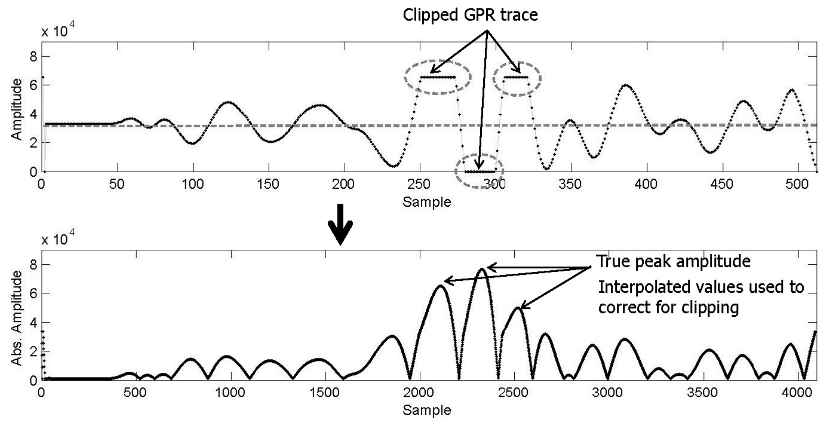

Figure 1: Example of how the interpolation function can be used to correct the clipped form of the traces.

With the interpolation the clipped wave parts have been corrected (Figure 1). We also use interpolation to obtain a finer data discretization. Thus, we carry the trace value from the original amount to a constant value (4096 samples/trace), which enables comparison between radargrams with different rates of capture (samples per trace). In addition, in this work we use the absolute wave amplitude values, which improve the final visualization because agent stamina increases during the competition.

3. Experimental study

This section provides the implementation of the proposed method of WSS component evaluation from GPR radargrams using a multi-agent approach, as described in Section 2. The case-study corresponds to GPR images taken from a plastic pipe commonly used in WSS. The pipe material tested was PVC with a diameter of 0.10 m. The GPR image was obtained by burying the pipe in dry soil in the test tank. The following task consists in post-processing the captured GPR radargram using the proposed method. In Figure 2, some competition times are shown.

In Figure 2, we can observe the different agent reactions after the passing through the soil configurations. Thus, for the analyzed radargram the warming-up phase is not finished until time 475, and the first movement for the racing phase takes place at 476. Similarly, the grouping of agents in areas is observed after the competition is finished, and this corresponds to

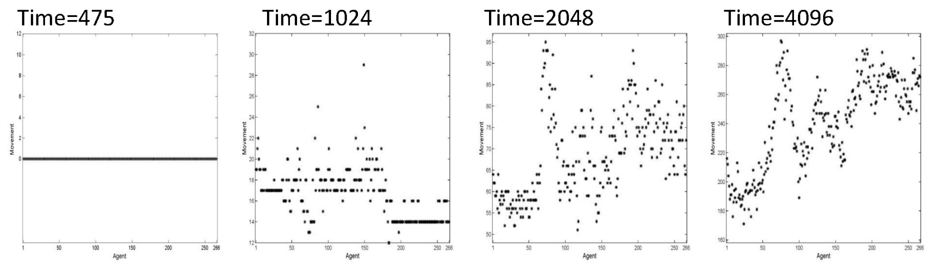

Figure 2: Some competition times.

the proposed test configuration. For a better interpretation, in Figure 3 we contrasted the last race time with the schematic configuration test proposed.

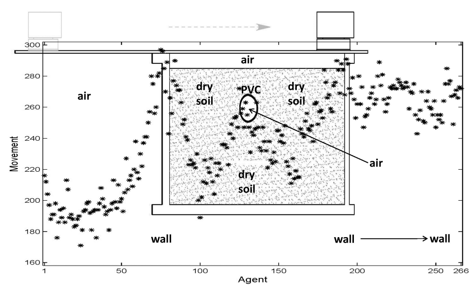

Figure 3: Last race time versus schematic configuration test.

In the last race time, the agent movements indicate, for the proposed test configuration, different velocity areas (Figure 3). In addition, the marked areas correspond to the soil velocities for the test: the materials for the tested soil being air, wall, dry soil, mixed area, dry soil and wall (from left to right). Moreover, the mixed area is the accumulation of velocities, since the air, dry soil, PVC, air, PVC and dry soil compose the mixed area (from top downwards). The movement times ($MovTi$) for each agent are rendered graphically and the result is shown in Figure 4, b. The input for the race (radargram) and the schematic test configuration are shown in Figures 4, a and c, respectively.

In the images shown in Figure 4, b presents a smaller number of points than the corresponding image in Figure 4, a, and thus enabling an easier interpretation. It can also be observed when comparing Figures 4, b and c, that obtained points with similar configurations also produce similar images.

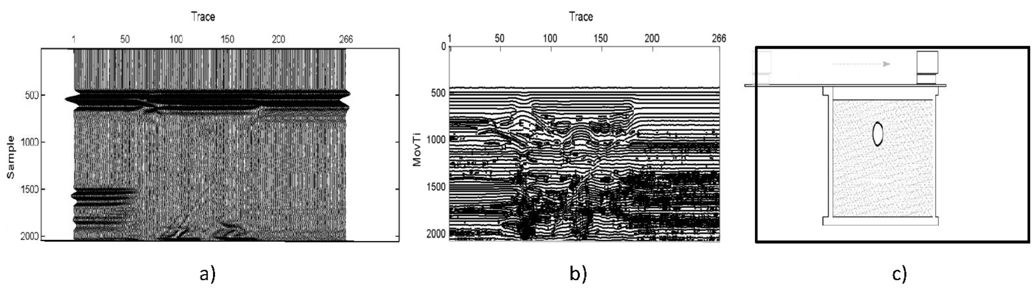

Figure 4: a) radargram, b) final image, and c) squematic configuration for test.

As a result, we can demonstrate that the application of the proposed multi-agent method improves insight into the subsoil properties.

4. Conclusions

In this paper we propose a tool for WSS component evaluation from GPR radargrams using a multi-agent approach. In the raw captured radargram without post-processing, we can see how the weakly reflective plastic pipe materials (PVC) are difficult to identify. The transformation of the raw data based on the proposed multi-agent method improves the visualization of plastic pipe images by producing a better representation of the signal characteristics. In general, it is much easier to see the pipe features in the GPR images. This procedure reduces the number of points that comprise the radargrams, and provides clear information for further intelligent processes. In each point obtained for the figures, the most relevant information for their environment has been grouped. The points can be visualized in a binary scale of colors (white and black), and thereby subjectivity in the choice of the color scale is eliminated.

Finally, it should be noted that this is a simple process that does not depend on specialist skills (thus being a non-subjective process) and is repeatable. The proposed multi-agent method is efficient with computational resources (even in the complicated case of plastic pipes). The amount of information dealt with has been reduced, while reliability is preserved. Moreover, the proposed method offers the possibility of more detailed analysis in terms of time with the movements of agents, and this creates the possibility of better interpretations that could serve as a basis for intelligent training systems. This approach would help give WSS managers a more accurate vision of the systems they operate and, as a result, offer a better service to users.

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