Time Based Radar Signal Analysis Revealing Nature and Properties of Surface Scans

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Summary

To clarify subsurface properties, it is necessary to investigate the time base of the signal. However, it is often necessary to solve the problem of determining the structure of only the surface layer. Our method addresses this problem.

Advantages of the method:

1. Highlights homogeneous areas in terms of surface conditions

2. It can process large data on profile measurements in an almost continuous mode, using any one (or a small amount) information signal attribute.

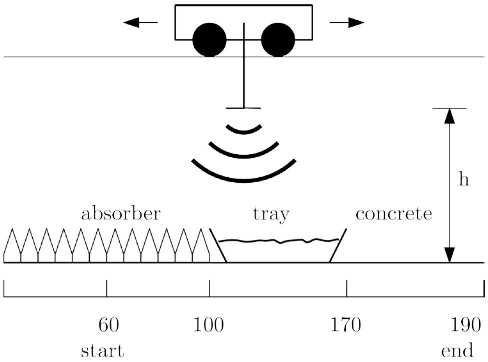
3. There is no need for desk data processing, interpretation.

4. This method uses a signal of any nature.

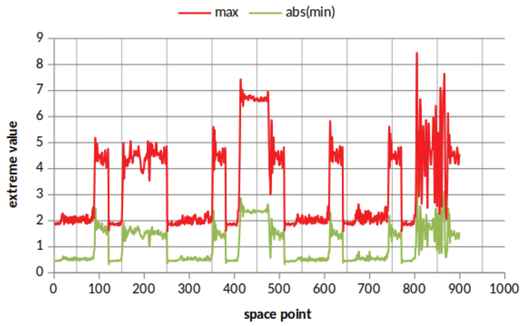
Here we explore if it is possible to obtain more information about the quality and state of the object by not only looking at a single time-based measurement, but instead looking at consecutive measurements as from a stream. By studying the structure of the stream and the changes in it, properties like moisture content can be revealed. A method is proposed for fingerprinting radar signals and detecting the boundaries of homogeneous media during a scan along changing objects properties.

Introduction

There is a need for obtaining information on the quality of monitored media. One such an application would be monitoring of road conditions; snow, ice, water film, and grip Ng et al. (2019), Arbabpour Bidgoli et al. (2019). In control systems for products where a drying process is involved such as food, chemicals, paper, minerals and textiles, a sensor that can give realtime information on the moisture can be invaluable Khamtree et al. (2019). A more far fetching application would be to do remote sensing of a 'plastic soup collection systems' Serranti and Bonifazi (2019)Further experiments are needed to find out if the latter is possible with current system. Here we are presenting the method, algorithms involved and experiments scanning materials at a certain distance below the radar. The task of on-line monitoring by non-invasive



(a) Experimental setup



(b) Behavior of extrema

Figure 1: a) Experimental setup. Radar is mounted under a cart that can be moved on a rail. Radar is moved along rail and has a beam angle of about 30 degrees. Measurements are taken at constant intervals of along the horizontal at stationary points. b) Behavior of maxima (red) and minima (green) for model flow F_l.

methods of the state of the material moving along the conveyor belt is currently being solved in different ways Bartelt (2011), Irudayaraj and Reh (2007) and Murugesan (2006).In this paper, we propose using the signals of the integrated radar ystem reflected from the surface and the APFLOW algorithm Kataev (2012) as a data processing method for this purpose. The APFLOW algorithm was previously developed by the authors to determine the structure of a stream of homogeneous random events or to approximate it by a Markov Chain flow (a flow with switching) Bekkerman et al. (2013). Adapted APFLOW variants were used to solve a variety of problems, in particular, to interpret the data of downhole research using the **gamma-ray** logging method Miller. et al. (2019). When scanning a material, the signal reflected from the objects changes randomly, both due to fluctuations in the distance between the radar and the surface of the object, and due to a change in the state of the object. If the materials or sensor move at a constant speed v, and a radar placed above it at a certain height captures the reflected signals after a time dt, then we have information at points $x_1, x_2, \ldots$, the distances between which are $\Delta x = v\Delta t$.

To use the APFLOW method, it is necessary to associate one value for each measurement at a spatial point, which we will refer to this as information fingerprint or just fingerprint. Then the values of this attribute can be represented in the form of a time-ordered series of numbers $n_1, n_2, \ldots, n_M$, which we will call the measurement flow. Even for a homogeneous medium, due to the presence of noise, this stream will be a sequence of random numbers oscillating around its average value. In the case where sections containing different materials (or different states of the same material) fall into the flow, fluctuations will occur near different average values. To find an information fingerprint, experimental studies were conducted in which the signals reflected from different media were studied. Studies have shown that the extreme values can act as fingerprints of reflected signals Obeid et al. (2009), Karrenberg (2002) and Schultz (2015). The received reflected signals from different media in a different number of spatial points allowed us to create a variety of data streams, modeling this or that real situation. As an example, Fig. 1b shows the maximum and minimum (in absolute value for ease of comparison) values of signals received from different media for flow F_1. It can be seen that the extremes behave synchronously; therefore, either its maximum, or minimum, or their difference can be taken as an information fingerprint of the signal. It is clear that the average value of the information feature in each homogeneous section depends on the physical properties of the medium, and its variability depends on the degree of surface roughness.

Experimental Setup

Staal Technologies' RIC60A has been used as a radar sensor. RIC60A is a 60 GHz BiCMOS single-chip millimeter-wave frequency modulated continuous wave (FMCW) radar with on-chip integrated antennas with analog and digital outputsAdela et al. (2016). The radar module scanned changing material surfaces. At discrete points a stationary measurement is taken. The absorber on the left and the concrete floor on the right provide a baseline to the measurements done on the materials laid in the a tray of uniform size. The object material in the tray gave such a uniform response that it is warranted to use sections of changing materials that give the impression of changing materials under the radar. The lhs of Fig. 2 shows a time scan of a typical reflected IF-signal, in this case from a concrete surface. A range profile can be obtained via FFT as is shown on the rhs in Fig. 2.

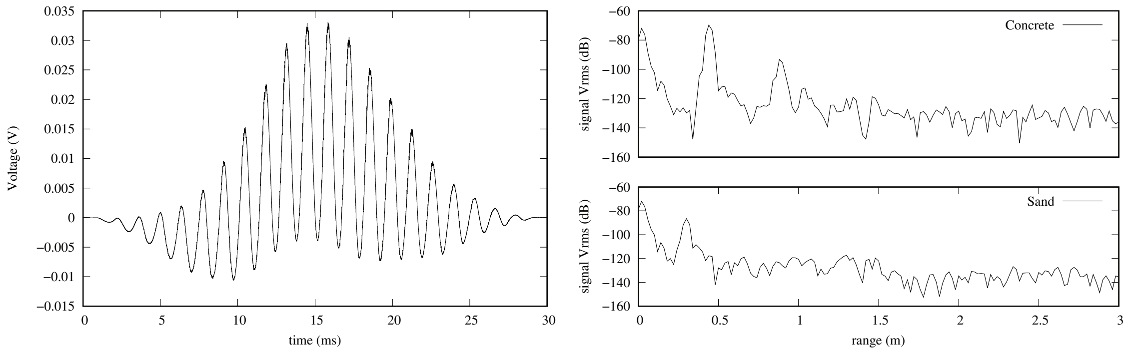


Figure 2: Time scan of typical IF-signal reflected from the surface is shown on the lhs. The two figures on the rhs show range profiles of concrete and sand. Concrete is at 47 cm from the radar, and sand is at 36 cm.

APFLOW Algorithm

APFLOW algorithm - a modification of the Method of Revealing Structures (MRS) Kataev (2012)- was developed to solve one of the main tasks of the queuing system - determining the structure of the event stream, meaning a sequence of homogeneous events that follow one after another at random times. Moreover, all events are equal, and each event is characterized only by the moment of its onset. The stream is characterized by intensity - the frequency of occurrence of the event or the average number of events that enter the device per unit of time. For the simplest Poisson stream, the intensity is approximately the same for any of its sections. A more complex Markov Chain flow (MC flow) can be represented as a sequence of simple (Poisson) flows with a certain intensity. APFLOW allows you to approximate a stream of random events by an MC flow. The problem of approximating an arbitrary stream of N events by an MC flow reduces, in fact, to finding its *structure* i.e., such moments of time τ_p, that the stream of events arriving for each interval $\tau_{m+1} - \tau_m$ would be approximately Poisson. It is customary to call such intervals *intervals of stationarity (IS)*. APFLOW is easy to adapt to the task of finding uniform layers during a scan. In fact, the fingerprints of signals are a series of random numbers $n_1, n_2, \dots, n_m$ and they can easily be represented as a stream of moments of occurrence of random events, if we assume that the quantities $n_1, n_2, \dots, n_m$ are analogous to the differences in the moments of arrival of neighboring events. The problem of determining the boundaries of the layers from the measured radar signals can thus be formulated as follows. Find the numbers of samples $m_j, j = 1, \dots, k$, where k is the number of layers separating different ISs. We maintain this concept, understanding by IS the sequence of consecutive numbers of a series, and their density function distribution obeys the Poisson distribution.

To find IS it is necessary and sufficient to build a matrix of relations between objects. The objects in the problem are the numbers of spatial points x_i, i=1,...N, and the intensity values i.e., values of the information fingerprint of the signal t_i, $i=1,\ldots N$.. In order for the flow to be ordered, the values of t_i are constructed recursively, i.e.

$$t_i = t_{i-1} + n_i \tag{1}$$

Moreover, as can be seen from 1, the difference between two adjacent values n_i is simple. As a characteristic of the relationship between objects (events) i and j, it is convenient to choose the distance between them i.e., the quantity d_{ij} determined by 2.

$$d_{ij} = \begin{cases} \frac{t_{j+1}-t_{i-1}}{j-1+1} & i \le j; i,j = 1,\ldots,N \\ 0 & i > j; i,j = 1,\ldots,N \end{cases} \tag{2}$$

The elements d_{ij} defined in this way form an upper triangular matrix $D = [d_{ij}]_{N\times N}$. We associate with each i^{th} event of the stream, $i = 1,N$, a vertex with the same number i of some graph G_k=(V_k,E_k), where V is the set of vertices of the graph of cardinality N, and E is the set of pairs of vertices i.e., set of edges of the graph. The cost of each edge of the graph connecting the i^{th} and j^{th} ($i < j$) vertices is the quantity d_{ij} i.e., the corresponding element of the matrix D. The cardinality of the set of edges of the graph is $N(N-1)/2$. Further, since MRS (and APFLOW) look for predefined structures on the graph, it is necessary to determine what is the structure in this problem. The definition of the structure can be formulated based on the concept of the stationarity interval. Namely, if a group of events with numbers $i_1^p, i_2^p, \ldots, i_k^p$ makes up a stationarity section of a stream with intensity $\lambda = \lambda_p$, then this means that

(a) the average value of the costs of all the edges connecting thevertices with the numbers $i_1^p, i_2^p, \ldots, i_k^p$, isapproximately equal to the intensity λ_p:

$$\frac{2}{k(k-1)} \sum_{(i,j\in I)} d_{ij} \cong \lambda_p \tag{3}$$

,

where I is the set of all kinds of pairs ordered by numbers from $\{i_1^p, i_2^p, \ldots, i_k^p\}$;

(b) numbers, i_j^p, $j = 1,k$, go in a row i.e., $i_j^p = i_{j-1}^p + 1$

(c) all $d_{ij}, i, j \in I$ belong mainly to a certain interval $(\lambda_p - \Delta\lambda, \lambda_p + \Delta\lambda)$.

The method is iterated. At the first iteration, the matrix D is scanned and all ICs that unconditionally satisfy the structure requirement are found. Then, from the graph, all edges connecting the vertices belonging to different ISs are removed, and the next iteration is performed. The quality of the partition is estimated by calculating the degree of reliability of the correspondence of the found ISs with Poisson using the Pearson criterion in the presence of a sufficient number of events in the IS.

As an example, Fig. 3 shows the flow of model data $F2$ of fingerprints composed of various media (concrete floor, empty tray, sand and sawdust of various degrees of moisture, etc.). The solid line shows the result of the APFLOW - found ICs.

Conclusions

1. At the first iteration, the APFLOW method distinguishes well the boundaries of objects in the presence of sufficient contrast in the amplitude of the reflected signal of the contacting media.
2. Clarification of the boundaries, if necessary, requires a second and, possibly, subsequent iterations. The first iteration can be performed in automatic mode, the subsequent ones in interactive mode.
3. The degree of detail of the allocation of ICs is regulated in the APFLOW method by controlling parameters, which makes it possible to isolate fairly short ICs.

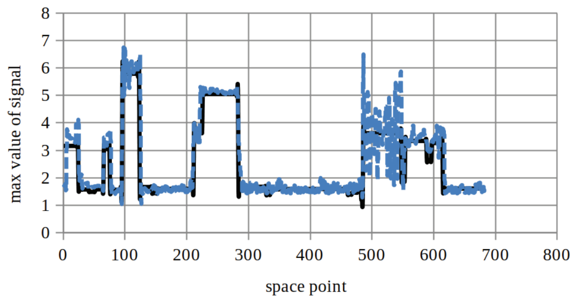


Figure 3: The behavior of the maxima (blue dashed line) for the model flow F2. Black line - average values (intensities) of the selected ISs by the APFLOW algorithm.

References

Adela, B.B., van Zeijl, P.T.M., Johannsen, U. and Smolders, A.B. [2016] On-Chip Antenna Integration for Millimeter-Wave Single-Chip FMCW Radar, Providing High Efficiency and Isolation. *IEEE Transactions on Antennas and Propagation*, **64**(8), 3281–3291.

Arbabpour Bidgoli, M., Golroo, A., Sheikhzadeh Nadjar, H., Ghelmani Rashidabad, A. and Ganji, M.R. [2019] Road roughness measurement using a cost-effective sensor-based monitoring system. *Automation in Construction*, **104**, 140–152.

Bartelt, T.L.M. [2011] *Industrial automated systems: instrumentation and motion control*. Delmar/Cengage Learning, Clifton Park, NY. OCLC: ocn670468277.

Bekkerman, E.N., Kataev, S.G. and Kataeva, S.S. [2013] Heuristic approximation method for a random flow of events by an MC-flow with arbitrary number of states. *Automation and Remote Control*, **74**(9), 1449–1459.

Goddijn-Murphy, L. and Williamson, B. [2019] On Thermal Infrared Remote Sensing of Plastic Pollution in Natural Waters. *Remote Sensing*, **11**(18), 2159.

Irudayaraj, J. and Reh, C. (Eds.) [2007] *Nondestructive Testing of Food Quality*. Blackwell Publishing Ltd, Oxford, UK.

Karrenberg, U. [2002] Introduction. In: *An Interactive Multimedia Introduction to Signal Processing*, Springer Berlin Heidelberg, Berlin, Heidelberg, 1–10.

Kataev, S.G. [2012] *Algorithmic and software of analytical and noninvasive control of parameters of the environment based on a method of detection of structures.* Ph.D. thesis, ational research Tomsk Polytechnic University, Tomsk.

Khamtree, S., Ratanawilai, T. and Nuntadusit, C. [2019] An approach for indirect monitoring of moisture content in rubberwood (*Hevea brasiliensis*) during hot air drying. *Drying Technology*, **37**(16), 2116–2125.

Miller., A., Kataev, S. and Kataeva, S. [2019] On a New Method of Detecting Layer Boundaries at the Borehole Measurements by Gamma Logging. The Hague.

Murugesan, R. [2006] Evolution of industrial automation. *International Journal of Computer Applications in Technology*, **25**(4), 169.

Ng, J.R., Wong, J.S., Goh, V.T., Yap, W.J., Yap, T.T.V. and Ng, H. [2019] Identification of Road Surface Conditions using IoT Sensors and Machine Learning. In: Alfred, R., Lim, Y., Ibrahim, A.A.A. and Anthony, P. (Eds.) *Computational Science and Technology*, 481, Springer Singapore, Singapore, 259–268.

Obeid, D., Sadek, S., Zaharia, G. and El Zein, G. [2009] A tunable-frequency system for touch-less heartbeat detection and HRV extraction. In: *2009 International Symposium on Signals, Circuits and Systems*. IEEE, Iasi, Romania, 1–4.

Schultz, W. [2015] Neuronal Reward and Decision Signals: From Theories to Data. *Physiological Reviews*, **95**(3), 853–951.

Serranti, S. and Bonifazi, G. [2019] Techniques for separation of plastic wastes. In: *Use of Recycled Plastics in Eco-efficient Concrete*, Elsevier, 9–37.