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APPLICATION FOR METHANE GAS DETECTION AND MEASUREMENT USING ADAPTIVE TIME SYNCHRONOUS MOVING AVERAGE

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Abstract. Methane is a potent greenhouse gas originating from both natural and anthropogenic sources. Detecting and quantifying methane emissions is crucial for environmental protection and industrial safety. This paper presents a software application designed for methane gas detection and concentration estimation based on an adaptive time synchronous moving average **(**ATSMA**)** algorithm. The software integrates signal classification, preprocessing, and estimation of methane concentration using absorption pulse parameters. The proposed ATSMA algorithm enhances signal periodicity while effectively reducing noise, leveraging the zero–crossing rate (ZCR) property to optimize averaging cycles. The processing workflow involves multiple steps, including initialization, gas classification, ATSMA filtering, multiband decomposition and absorption pulse estimation. The graphical interface provides signal visualization in both time and frequency domains, displaying key methane parameters such as spectral harmonic ratios and absorption pulse characteristics.

Keywords: Methane detection, ATSMA algorithm, zero–crossing rate, signal processing, absorption pulse, environmental monitoring.

Introduction

Methane, a potent greenhouse gas, originates from diverse sources, encompassing both human activities and natural processes. Biogenic decay in wetlands and forests, as well as the organic waste decomposition in landfills [1], significantly contribute to methane emissions. In agriculture, livestock farming activities, particularly the digestion processes of animals such as cows, contribute to methane production. Land cultivation and water usage in agriculture also play a crucial role in methane generation. The extraction and transportation of fossil fuels, along with processes like coal production and natural gas utilization, represent additional sources of methane emissions. Even forest fires contribute to the escalation of methane levels as carbon from burning vegetation undergoes decomposition.

The application for detecting methane leaks in pipelines is a promising endeavor in the fields of environmental monitoring and energy safety. This approach offers notable advantages, including the rapid and efficient coverage of large areas, leading to time and cost savings compared to traditional methods [2, 3]. In addition, methane detection is also used in medical diagnostics to assess gut bacterial imbalances [4]. To mitigate the greenhouse effect and ensure safety, identifying leaks and monitoring methane concentrations are urgent tasks.

This paper presents software designed to classify and detect signals containing methane while also analyzing and visualizing each step in the methane concentration estimation process. In software management, it is divided into four components (Figure 1): user interface, sequential processing, managing global variables and displaying information. The user interface is designed the QT Designer, a powerful graphical tool integrated with the Qt5 library, renowned for its robustness and versatility in creating cross–platform applications with seemingly appealing interfaces. This synergistic combination allows for the seamless design and implementation of intuitive interfaces tailored to the specific requirements of the project.

The sequential processing comprises seven steps: initialization, gas detection and classification, adaptive time synchronous moving average (ATSMA), multiband decomposition, pulse signal fusion rule, pulse fusion rule and estimation of absorption pulse parameters. Each step will utilize input variables and global variables from the preceding step.

The outcomes of each process are stored in distinct variables to streamline processing and facilitate the implementation of the back function. Following computation, the display variable is promptly updated to reflect the results.

The software interface (Figure 4) includes 3 parts: input information, graph display and output signal information. In Graph area displays each signal is displayed in two formats: time domain and frequency domain. The window "Information of signal" displays basic signal information and methane parameters. Basic signal information: length of signal, base frequency and sampling frequency. Methane parameters include spectral harmonic ratio features, absorption pulse parameters and estimated methane concentration.

The spectral harmonic ratio features include: root–mean–square base harmonic ratio (RMSBHR), even–to–odd harmonic ratio (EOHR), normalized spectral harmonic complexity (CH), spectral centroid (SC), harmonic noise ratio (HNR), HNR before adaptive time synchronous moving average (ATSMA) and HNR after ATSMA. Absorption pulse parameters: amplitude absorption pulse, area under absorption pulse, time–amplitude centroid area and frequency–amplitude centroid area. Methane concentration estimated according to amplitude absorption pulse, area under absorption pulse, time–amplitude centroid area, frequency–amplitude centroid area.

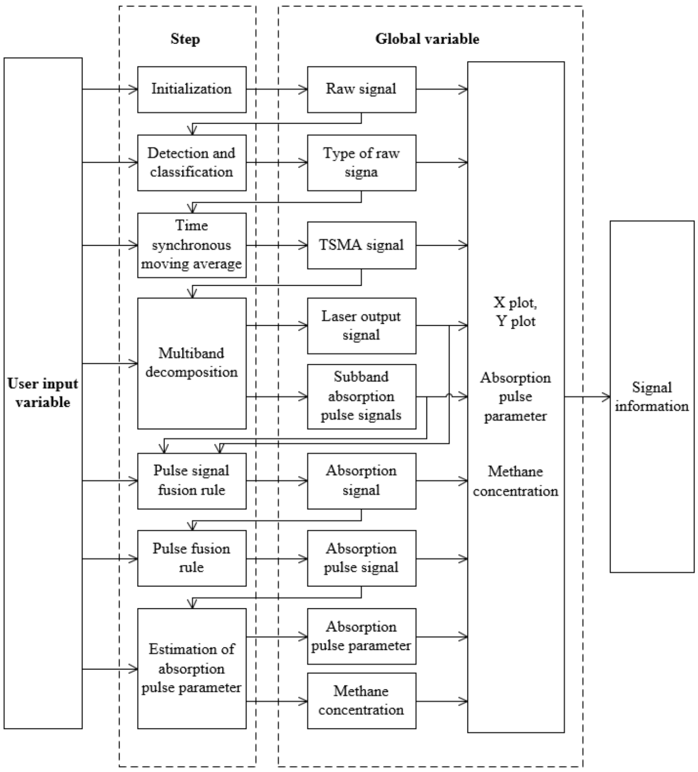

Figure 1. Software architecture diagram

An adaptive time synchronous moving average of the measured absorption signal

The time domain synchronous average (TSA) and the moving average (MA) are most commonly used average techniques in engineering [5, 6, 7]. TSA has the advantage at periodic signal detection by noise depressing and asynchronous signal components. The MA is effective to remove noises while keeping signal periodicity. However, the TSA signal is not periodic as measurement signal, and signal spectrum resolution degrades seriously, meanwhile, the MA filters out high–frequency signal components of interests. Time synchronous moving average (TSMA) method (Figure 2) combines the advantages of the above two methods keeping signal periodicity and high frequency signal components

[8]. The TSMA operates by averaging over M neighboring cycles of the measured signal, which has a total of N_c cycles.

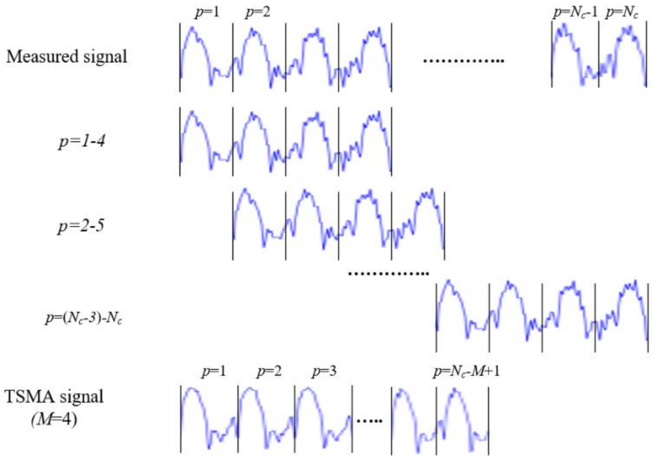

Figure 2. Illustration of time synchronous moving average (TSMA) algorithm

In [8] authors considered the TSMA filter to be optimal when the filtered signal had balance between spectrum resolution and noise gain. However, in this problem we are more interested in the periodicity of the signal. Because the methane concentration is constant over time, the received signal is theoretically characterized by periodicity.

Zero–crossing rate (ZCR) is a feature commonly used in signal processing to assess the periodicity of a signal [9, 10]. The ZCR can be defined as the number of crossing the signal the zero axis within a specific time frame (window). ZCR can be interpreted as a measure of the noisiness of a signal as ZCR values are higher for the noisy portions of the signal.

The block diagram of the proposed ATSMA algorithm based on the proposed model of the absorption signal, moving average and ZCR property is shown in Figure 3.

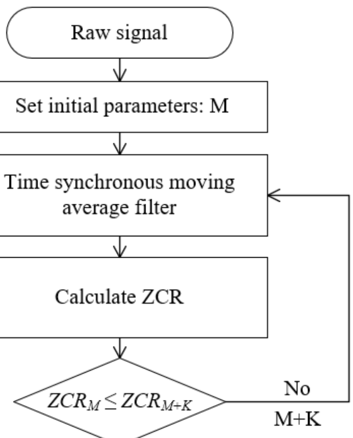

Figure 3. Block diagram of adaptive time synchronous moving average algorithm

The initial number of neighboring cycles $M \in (1, N_c)$ should be set during the first iteration, and then incremented after each subsequent iteration. To stop the iterative process of the algorithm is needed the termination criterion. The stopping criterion is determined by the interrelation between the number of time samples N, the time cycle samples N_S the total cycles N_c and the processed neighboring cycles M_{ZCR} of the absorption signal. This approach is likely suitable for signals with periodic components, and the effectiveness of the denoising process is determined by the stability of the zero–crossing rate.

The choice of the optimal averaging times would then be based on finding a balance between denoising effectiveness and time complexity.

Application for methane gas detection and measurement

This section introduces a software application developed for methane gas detection and concentration measurement, utilizing an adaptive time synchronous moving average (ATSMA) algorithm. The software interface is presented in Figure 4.

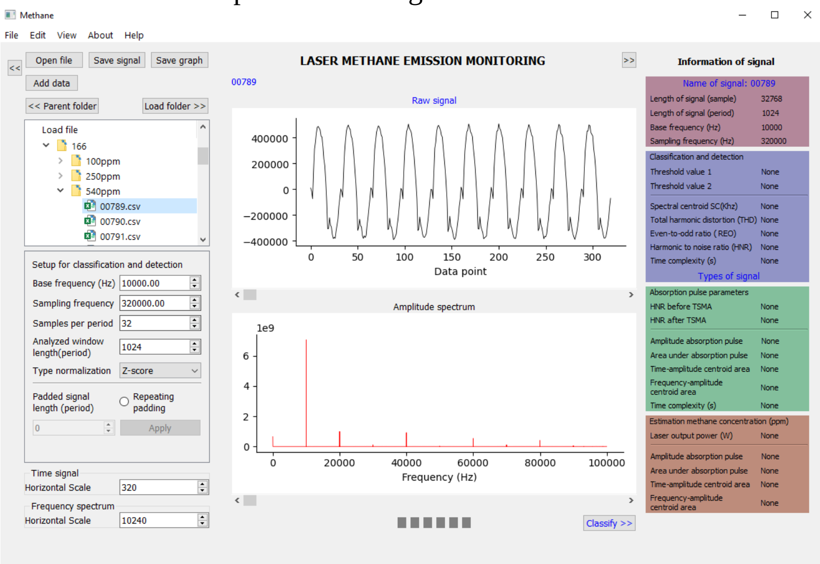

Figure 4. Main window of the methane gas analysis application

The main window of the methane gas analysis application (Figure 4) provides an intuitive interface for users to load, process and analyze methane signal. The following steps outline the initial workflow for interacting with the software:

1. Click the "Open file" button to open a new signal.

2. After pressing the open file button, a window appears to select the signal file to open.

3. For files containing many signals, after selecting, a window will appear asking to select the type of signal you want to process.

4. Enter input parameters: base frequency (Hz), sampling frequency, analyzed window length and type normalization. Click "Classify" button to classify and detect methane signals. After completion a window appears indicating the type of signal. Click "OK" button to continue.

5. Enter information about *M* neighboring cycles (averaging time), then click "Next" button to start the time synchronous moving average (TSMA) process. Then on the graph window appears the signal after TSMA and its amplitude spectrum.

6. Enter input parameters for multiband decomposition: *K* subband, order of filter and bandwidth of filter. Click "Next" button to run multiband decomposition of an adaptive average absorption signal.

7. Click "Next" to continue, on the graph shows absorption signal and amplitude spectrum of it.

8. Enter input parameters for pulse fusion rule: band width of pulse and calibration. Click "Next" to continue, on the graph shows absorption pulse signal and amplitude spectrum of it.

9. Select laser output power and then click "Next" to final step. Conclude absorption pulse parameters and methane concentration are obtained show on information window of signal (Figure 5).

Figure 5. Absorption pulse parameters and methane concentration

Conclusion

Methane detection and concentration estimation are essential for environmental protection, industrial safety, and medical applications. This paper introduced a software application utilizing the adaptive time synchronous moving average **(**ATSMA**)** algorithm to estimate the accuracy of methane signal classification and concentration estimation. The ATSMA method effectively suppresses noise while preserving signal periodicity by incorporating the zero–crossing rate (ZCR**)** as a stability criterion.

The developed system offers a comprehensive solution with a structured processing pipeline, including signal classification, adaptive filtering, multiband decomposition, and absorption pulse parameter estimation. The user–friendly interface enables visualization of signal characteristics in both time and frequency domains, providing valuable insights into methane signal properties.

This approach can be applied in various fields, including environmental monitoring, industrial leak detection and medical diagnostics.

References

1. He H., Gao S., Hu J., Zhang T., Wu T., Qiu Z., Zhang C. // Applied Sciences. 2021. Vol. 11. P. 2117–2125.
2. Iwaszenko S., Kalisz P., Slota M., Rudzki A. // Remote Sensing. 2021. Vol. 13. P. 510–518.
3. Angus G., Steven D., Kyle J., Miles J., Graham M. // Proceedings of the SPIE. 2023. Vol. 12795. P. 1279503.
4. McKay L.F., Eastwood M.A., Brydon W.G. // Gut. 1985. Vol. 26. P. 69–74.
5. Braun S. // Mechanical Systems and Signal Processing. 2011. Vol. 25. P. 1087–1102.
6. Smith S.W. // The Scientist and Engineer's Guide to Digital Signal Processing. 1991. P. 277–284.
7. Hassan U., Anwar S. // Eur. J. Phys. 2010. Vol. 31. P. 453–459.
8. Zhang L., Hu N. // IEEE Access 2019. Vol. 7. P.93035–93048
9. Gouyon F., Pachet F., Delerue O. // Proceedings of the COST G–6 Conference on Digital Audio Effects. 2000. Vol. 5. P. 16–20.
10. Deshmukh O. and Wilson C. E. // IEEE International Conference on Acoustics, Speech, and Signal Processing, 2003. Vol. 1. P. 1–4.