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Time-Frequency Analysis and Applications

Approximately 200 years ago, Fourier carried out his work on heat flow that culminated in 1811 in his celebrated memoir, where he claimed that any function of a variable, whether continuous or discontinuous, may be expanded into a series of sines of multiples of the variable. A report at the time from a committee consisting of several contemporaries including Laplace and Lagrange concluded the following:

> ... the manner in which the author arrives at these equations is not exempt of difficulties and that his analysis to integrate them still leaves something to be desired on the score of generality and even rigour.

This comment, attributed to Laplace, was specifically referring to the issue of discontinuities. Such difficulties have since been alleviated. The developments in harmonic analysis, rooted in solid mathematical foundations and equipped with efficient algorithms [e.g., fast Fourier transform (FFT)], have made Fourier methods universal tools in almost all branches of science and engineering. It was soon realized that in regard to its physical interpretation, Fourier analysis was aimed at stationary situations, in contrast with most observations of real-world systems. Consequently, making Fourier methods time dependent has become a necessity.

In time-frequency (TF) analysis, a function whose domain is the two-dimensional real plane is obtained from the signal via a transform that can be viewed as a time-dependent extension of classical Fourier-based methods. The motivation generally lies in attempting to understand the time-varying structure of many signals that we encounter, as well as to enable manipulatation of these signals in the proper domain that is better suited to their nature of nonstationarity. There is, however, no unique way to define a TF transform; this topic has been the subject of many thorough investigations over the past 30 years, culminating in today's "classical" approaches (based on either short-time Fourier transforms, wavelets, or Wigner-type energy distributions, to name just a few) that are routinely used in many domains. More recently, there have been important revisits to these questions that offer new perspectives, serve emerging applications, and are driven by new developments in signal analysis, synthesis, and reconstructions. In this special issue of *IEEE Signal Processing Magazine*, we review the current state of the art in this field, consider open problems, and highlight new important applications.

The articles in this special issue fall into two categories: the first category presents the underlying methodology and theoretical approaches of TF analysis, and the second considers the role of TF methods in several application domains.

The first set of articles, as indicated above, can be considered as dealing with methodological issues, although they all illustrate their work with extensive use of signals from a wide variety of applications, e.g., audio, radar, sonar, and physiological signals.

Balazs et al. deal with concepts in adaptive linear TF representations, transform, as well as coefficient domain modeling, with consideration of the impact of sparsity. The article makes use of examples from audio signals to illustrate the methods.

Auger et al. consider synchrosqueezing tools and their relationship to reassignment methods with examples from the biological domain (bat chirps), and physiological signals, i.e., anesthesia-related signals.

The article by Chaparro et al. considers the use of asynchronous representations for nonstationary signal analysis and its relation to nonuniform sampling. Next, Napolitano discusses the relationship between cyclostationary methods and TF analysis with applications in radar and sonar to illustrate the methods. Continuing on, Angelosante et al. consider sparsity-aware TF tools for nonstationary signal analysis and time-adaptive (online) algorithms using electroencephalography signals as an example.

Empirical mode decomposition is a data-driven analysis method that has attracted significant interest over the last decade. In the article by Mandic et al., the various recent advances and refinements are presented and discussed with illustrations on a variety of application signals.

The article by Matz et al. provides an important link between the two elements of the articles in this special issue, as it is driven by a need within the communications arena for characterization of communication channels but is firmly embedded within a sound methodological approach of TF methods.

The article by Belouchrani et al. moves us solidly into the application domains by illustrating how TF methods can offer significant performance advantages. It shows how TF distributions can enable source localization and separation in radar and communication applications.

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application is expected out of the classroom, and this forced, supervised extra practice directly translates to improved exam performance. A casual approach to watching video lectures outside of class is likely of much less negative consequence in a flipped classroom than a half-hearted approach to working problems out of class in a conventional paradigm. Even those who are diligent in working on problems on their own are likely to get "stuck" applying new concepts, while they quickly get their questions answered in the flipped classroom.

This flipped classroom experience has changed a subconscious view that I held for 25 years regarding the capability of undergraduate students to master signal-processing material. I had consistently observed a stubborn 40% or so of my signal-processing and signals and systems classes fail to demonstrate what I considered proficient use of the material on the final exam, e.g., the 45% that scored below 70 in Figure 4(a). This happened in spite of my best efforts and the fact that I usually scored very high on student evaluations of my teaching, so I assumed that a significant fraction of students simply were not able to learn signal processing at a high level. This view was manifest in the curve I used for grading, which typically had the top 15% of the class receiving As, the next 30% receiving Bs, and the remaining 50+% Cs or lower with a class average grade point average below three out of four. My experience with flipping the class has made it abundantly clear that the critical issue is not the ability of the students, but rather the method of instruction. The overwhelming majority of students really are capable of mastering signal processing. My job as a teacher is to engage them in a way that enables them to perform at a high level. The high level of performance I observed led to an unexpected dilemma assigning grades. Following my historical curve would have led me to give different grades based on nearly indistinguishable performance differences. I concluded this was a very good problem to have and decided to assign grades based on my assessment of absolute performance instead of relative performance. Consequently, a very large majority of the class received As or Bs.

There is room for improving the approach used in these first two classes. Specifically, student feedback suggests that the difficulty and duration for the in-class exercises and amount of out-of-class homework requires additional adjustment. I am also adding brief automated quizzes on each lecture using the course management system. They are designed to be completed prior to class, and quiz performance will be a small component of the performance evaluation. The primary goal is to increase retention of key concepts. Quiz performance also provides a near real-time metric of student engagement and progress, allowing the instructor to quickly identify students that are struggling and initiate intervention.

I have taught at UW-Madison since 1987. Flipping my classes has been the most transformative experience of my career, and I doubt that I will ever be able to go back to teaching in the conventional paradigm, especially for undergraduate- or introductory graduate-level signal-processing classes. I too have flipped.

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REFERENCES

[1] A. King, "From sage on the stage to guide on the side," *College Teach*., vol. 41, no. 1, pp. 30–35, 1993.

[2] M. J. Lage, G. J. Platt, and M. Treglia, "Inverting the classroom: A gateway to creating an inclusive learning environment," *J. Econ. Educ*., vol. 31, no. 1, pp. 30–43, 2000.

[3] J. Foertsch, G. Moses, J. Strikwerda, and M. Litzkow, "Reversing the lecture/homework paradigm using eTEACH Web-based streaming video software," *J. Eng. Educ*., vol. 91, no. 3, pp. 267–274, 2002.

[4] [Online]. Available: http://www.techsmith.com/camtasia.html

[5] Wisconsin Collaboratory for Enhanced Learning. [Online]. Available: http://www.wiscel.wisc.edu

[6] B. Van Veen. (2013, July 15). "Preparing a lecture with Photoshop and Camtasia." [Online]. Available: http://www.youtube.com/watch?v=q3-NqjtSn7Y

[7] B. Van Veen, "AllSignalProcessing." [Online]. Available: http://www.youtube.com/user/allsignalprocessing

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The next article by Boashash et al. provides a description of the application of TF methods to the analysis of electrocardiography and fetal movement signals with the aim to develop automatic analysis and classification methods for such signals.

The final article by Bonnel et al. focuses on the use of TF representations in the analysis and characterization of underwater acoustic channels.

We hope that this special issue provides the reader with a broad scope of theory and applications of TF signal analysis, capturing recent developments and opening the door to new frontiers. The nonstationary nature of ubiquitous biological and man-made signals will continue to fuel the interest in this area and propel future contributions to improved representations that meet problem–solution objectives and are specific to different applications.

We would like to express our deep gratitude to the many individuals who made this special issue possible. We thank all of the authors who submitted proposals and all of the reviewers whose recommendations significantly helped in improving the selected articles. We are also indebted to *IEEE Signal Processing Magazine* Editor-in-Chief Abdelhak Zoubir and Special Issues Area Editor Fulvio Gini for their support and guidance throughout the solicitation and reviewing process, as well as to Rebecca Wollman for her valuable administrative assistance.

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