# Applications Wavelets in Industry - Patenting Trends

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*Abstract* - During the past decade, a variety of highly pragmatic applications have been developed based on wavelet theory. Evidence of the impact of this trend on industry is the increase in patents based on wavelet technologies that have been filed in the United States. We examine numerical counts of annual patent filings and examine the some noteworthy practical applications.

*Key-Words:* - Wavelets, Wavelet Transform, Time-Frequency Analysis, Multiresolution Analysis

## 1 Introduction

*"Wavelets are families of functions $h_{a,b}$:*

$$h_{a,b} = |a|^{-1/2} h\left(\frac{x-b}{a}\right) \;\; ; \quad a, b \in \mathcal{R} \; , \; a \neq 0$$

*generated from a single function h by dilations and translations"* [6]. One of the applications of the theory is to construct a basis set $\{h_{a,b}\}$ for efficient and accurate approximation of functions, operators, and signals at varying degrees of accuracy using *multiresolution analysis* (MRA) [27].

A second class of applications involves the use of wavelet transforms (WTs) for time-frequency analysis of non-stationary signals [33]. For wavelets with mother function $h$, the *continuous wavelet transform* for a function $f \in L^2(\mathcal{R})$ is defined as

$$\langle h_{a,b}, f\rangle = |a|^{-1/2} \int dx \cdot h\left(\frac{x-b}{a}\right) \cdot f(x),$$

where $a, b \in \mathcal{R}$, $a \neq 0$, and the *discrete wavelet transform* is defined as

$$\langle h_{m,n}, f\rangle = |a_0|^{-m/2} \int dx \cdot h(a_0^{-m} x - n b_0) \cdot f(x),$$

where $a_0 > 1$, $b_0 \neq 0$ [7].

Many signal processing applications use convolutions with filter bank coefficients rather than the wavelet function [28]. A *filter* is a linear, time-invariant operator that acts on an input vector $x$ to produce a vector $y$ by convolution of $x$ with a fixed vector $h$, i.e.,

$$y(n) \;=\; \sum_k h(k) \cdot x(n-k) \; , \; n \in Z \; ,$$

where $x(n)$ and $y(n)$ are the values of (signal) $x$ and $y$ at times $t = nT$; $h(n)$ are the *filter bank coefficients*; and $T$ is the *sampling period*.

A third area in which wavelets have made an impact is in the study of differential equations – mathematical analysis, operator theory, and mesh generation. There are many types of wavelets and wavelet-based techniques. The optimal choice of wavelet type and method depends on the specifics of the application.

In the next section we present results from patent searches using the keyword *"wavelet"* along with speculation on current and possible future trends involving patent filings. In the third and final section of the paper, we present examples of practical applications of wavelet analysis. Since research on wavelets has become so prevalent, a comprehensive survey on industrial applications is impossible. We present some interesting examples in the hope that they will give prospective wavelet researchers some insight into new approaches to analyzing data.

## 2. Wavelet-Related Patents

Quantitative evidence of the impact of wavelets on industry is the increase in patents based on wavelet technologies that have been filed in the United States in the past two decades. Although initially, wavelet patents focussed on seismic and echographic signal analysis for mineral and resource recovery (e.g., the first wavelet-related patent *"Wavelet Standardization"* by Atlantic Richfield Company in 1971 [10]), more recent filings cover a wider range of applications, such as image and signal processing, medical signal analysis for diagnosis, and monitoring systems for maintenance and manufacturing. Also noteworthy are a number of algorithms for pattern recognition, computer graphics and visualization.

We ran a search engine on the United States Patent and Trademark Office (USPTO) Web pages [1] using the keyword "*wavelet*" either in the title or abstract and found that the number of patent filings is steadily increasing, as can be seen in Table 1 and Figure 1. Values for the year 2001 were compiled on Sept. 25, 2001 and normalized to a full year by multiplying by the factor 365/268.

**Table 1:** Annual number of patents issued with keyword "*wavelet*" in title or abstract

| year | no. | year | no. |
|---|---|---|---|
| 1980 | 2 | 1993 | 3 |
| ... | ... | 1994 | 2 |
| 1986 | 3 | 1995 | 13 |
| 1987 | 3 | 1996 | 19 |
| 1988 | 3 | 1997 | 30 |
| 1989 | 1 | 1998 | 50 |
| 1990 | 2 | 1999 | 46 |
| 1991 | 1 | 2000 | 55 |
| 1992 | 2 | 2001 | 97 (71) |

Various interpretations of the patent counts are possible. One is that patent filing and upkeep is costly so that the counts must accurately reflect the impact a technology has on businesses. A skeptical view is that the numbers alone mean very little since the filings rook place during a period when some claimed zealous, overselling of wavelets was taking place [40]. An interesting property of the counts is the difference in the results of searches performed at different times using the USPTO homepage. When we ran the same search in 1999, 2000 and 2001, creasingly fewer documents were retrieved at later dates, indicating that some refinement of the search procedures has been undertaken, some were withdrawn, or some did not receive support of maintenance costs from the inventors or the institutions with which they were affiliated.

[1] www.uspto.gov/patft/index.html

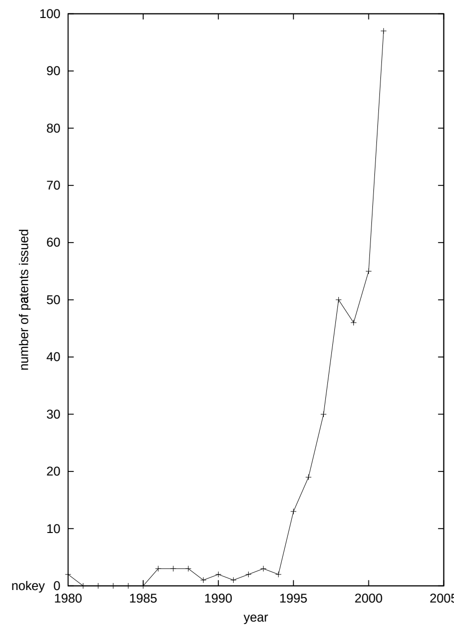


Figure 1: Number of U.S. patents issued with keyword "wavelet"in the title or abstract.

One of the most well-publicized examples of a successful wavelet-based technology is a a data compression technique for a new U.S. national standard for digitized fingerprint records Another practical example is the real-time, automatic classification of the quality of welds made by industrial robots [32]. Wavelet analysis and vector quantization are applied to current and voltage signals from gas metal arc welding robots. Experiments results indicate that the accuracy of the classifications are about 93%. An unusual example is a new, wavelet-based approach for browsing, visualizing and exploring unstructured text to determine the thematic content, generate fuzzy document outlines, summarize it by levels of detail and according to user interests, define meaningful subdocuments, query text content, and provide summaries of topic evolution [29].

## 3. Applications

Wavelets can be used to study data from perspectives from their traditional counterparts.

We give examples of new wavelet-based tools for time-frequency analysis, MRA, noise reduction, and solutions of differential equations, etc., that have been used to solve problems in industry.

### 3.1 Time-Frequency Analysis

Signals can be described in many different ways, however, good descriptions allow facile extraction of meaningful information for a particular purpose. Two fundamental variables in signal analysis are time and frequency. In many situations, these variables are analyzed independently, despite their known interdependency. Joint time-frequency analysis has been studied extensively and has been used as a standard tool for speech signal analysis, and recently, its value is receiving increased recognition by scientists in other fields, such as medical data analysis, manufacturing and machine monitoring, signature analysis, and financial analysis [33].

Fourier Transforms (FTs) have been used for time-frequency analysis of acoustic signals, and they have been successful, for the most part, however, some phenomena (e.g., small, non-periodic signals) have been elusive. During the 1980's, simple experiments indicated that wavelet analysis, i.e., time-frequency analysis of the WT of data, could be very useful for the detection of abrupt changes in non-stationary signals [25]. Unlike STFT analysis, WT analysis allows arbitrarily good frequency resolution for coarse time resolutions and arbitrarily good time resolution at high frequencies. For example, if a signal consists of two short bursts, the bursts can be separated during WT analysis if sufficiently high frequencies are used.

FT-based time-frequency analysis of speech signals have been represented in graphs known as scalograms and phase-shift displays, which are three-dimensional representations of signal spectra, with time represented on the x-axis and frequency on the y-axis. Color or gray scale maps are used to represent the third dimension, either amplitude (for scalograms) or phase (for phase-shift diagrams). Analogous time-frequency displays of WT data that are being used for signal analysis acoustical signals are useful because the WT is well localized in both the time and frequency domains and can be used for constant-Q analysis of a signal in the time-scale plane [33]. Experiments by several independent researchers indicate that WT analysis shows promise in speech event and word boundary detection and can be used to identify four categories of speech: voiced speech, plosives, fricatives and silence. A patent that has been filed for hearing aid devices using wavelet technology [38] is based, in part, on work on loudness compensation using wavelets [9].

A variety of pitch marking techniques have been developed over the years, and on-going research contributes to improvements in the field [12]. We modified a WT-based pitch marking method reported in [18] and developed software to detect glottal closure instants, that serve as reference points for accurate pitch marking. The method in [18] is based on the abrupt change in a speech waveform at glottal closure instants. We detect the glottal closure instant by searching for a local peak in the WT of the speech waveform and use it to estimate the pitch period. We use an adaptive threshold to stably and accurately extract the glottal closure using dyadic wavelets and determine the pitch period using the glottal closure instants. Block by block processing delays, that occur in implementations of the method in [18], are eliminated in our method. Furthermore, our method can be used for both male and female voices with no parameter changes.

Our method was adopted for marking pitches in speech synthesis units for a Japanese text-to-speech (TTS) product for personal computers [24]. The TTS system relies on the accurate placement of the marks for a overlap-add (OLA) process to generate a speech waveform, which will lead to natural sounding synthesized speech. Our OLA technique is an extension of [11]. The output from our pitch marking program was double checked when phoneme segmentation was performed manually. In contrast to conventional methods, which use transform extrema for pitch marking, our wavelet method uses the maxima of the transformed signal. Our method has a 97% success rate for identification of glottal closure instants [31], in contrast to the 95% success rate of the method in [30]. Other WT-based pitch-marking techniques are [19], [44].

A second application of acoustical signal processing using WT is separating different types of sounds [36]. This application is one of the many challenging problems which must be overcome in the development of next-generation speech recognition systems. Current systems require relatively background noise-free data, including the absence of music. Another fundamental problem in speech signal processing is that of speaker recognition, i.e., the ability to differentiate the size and shape of the (source) speaker. The stabilized wavelet-Mellin transform is used as one of the tools to differentiate characteristics of the speaker [16].

Wavelet-based time-frequency analysis is being used in a variety of disciplines other than speech to aid in manufacturing and signal analysis. Some of the more unusual scenarios include identification of: irregularities in cement mixes by *Chichibu Onoda*, a leading Japanese cement company [1]; irregularities in cooling system valves, the development of a WT-based time-frequency analyzer with a user-friendly Japanese interface, and the development of a system to compress *keisoku* (control and sensor) data in a manner which preserves features essential for automatic, pattern matching-based identification of irregularities in data at *Yamatake-Honeywell* [20]; problems associated with assembly line conveyer belts (roller slippage and object drift) in a joint project by by Toyohashi University of Technology and a Japanese manufacturer [15], [22]; and automobile engine defects in a joint project by a university and a leading Japanese automobile manufacturer [21]. The development of golf balls which emit a more professional and "sporty" sound when they are struck and driven off a tee at angles that have been targeted by pros by the Industrial Technology Center of Okayama Prefecture and a Japanese golf equipment manufacturer [45].

### 3.2 Noise Reduction

A straightforward application of Mallat's decomposition algorithm [27] was successfully used by Sakakibara to clean data from laboratory experiments commonly used by mechanical engineers: dry friction analysis and drop mass tests [35]. Wavelet techniques for "*simultaneous noise suppression and signal compression, classification, regression, multiscale edge detection and representation, and extraction of geological information from acoustic waveforms*" and a library of orthonormal wavelet Basis for signal feature extraction and signal compression have also been developed at Schlumberger-Doll Research [34].

A more sophisticated wavelet-based noise reduction method was developed by Kajima Corporation to clean noisy seismic acceleration data [43]; Japanese architectural firms commit extensive funds for research on seismic effects on buildings and structures. The scientists constructed new biorthogonal wavelets specially adapted for a class of integral operators. Seismic data correction is carried out in the time-frequency domain using the biorthogonal wavelets. This WT-based technique successfully identified and separated what were inextricably intertwined signal components and enabled correction of noisy data; the signals cannot be cleaned easily using conventional methods. Wavelet-based techniques for cleaning noisy data have also been reported by [5], [8], [13], [26].

### 3.3 Approximations and MRA

At the Earthquake Research Institute (ERI) of the University of Tokyo, Hiyama et al. developed a system to accurately display two-dimensional geographical data at user-specified resolutions on a personal computer using wavelet-based MRA [14]. More sophisticated wavelet methods for curve and three-dimensional map display are being developed for a variety of purposes, see, e.g., the annual *Proceedings of ACM SIGGRAPH* and [39].

### 3.4 Differential Equations

Wavelets are being used to solve scientific and industrial problems which are can be effectively modeled by differential equations. They are being used in many different roles, including mesh generation , preconditioning, and the development of new operators.

At the Nuclear Engineering Laboratory of Toshiba Corporation, scientists developed a powerful and simple new wavelet-based preconditioning method for solving large systems of linear equations [41]. The preconditioner leads to accurate results while substantially reducing computation time and costs in simulations of fluid flow modeled by Poisson equations. Preconditioning using wavelet bases leads to improved performance since conjugate gradients methods cannot prevent the exponential increase in computing time when the number of gridpoints is increased.

Scientists at the Disaster Prevention Research Institute of Kyoto University developed and applied a new wavelet to analyze how the topography of the region surrounding a large, man-made structure in Japan influences turbulent and potentially violent characteristics of high winds [42]. They developed a method for classifying WT coefficients from two distinct components of turbulent wind data. In a second study, when wavelet techniques were used to study Navier-Stokes equations, scientists found that the probability density function of the wavelet coefficients of the velocity data has a power-form in regions with very high wavenumbers, in the deep dissipation range [43].

Jameson at ICASE and Mitsubishi Heavy Industries developed then applied a wavelet-based grid generation technique to computational fluid mechanics at [17]. He has also studied appropriate weighting between computational and observational data and has applied his techniques to identify, label, and track eddies in Topix/Posseidon satellite data.

As discused above, the study of wavelets has shifted from a purely academic exercise to the development of practical solutions for product development and manufacturing. Undoubtedly, new contributions by wavelet technologies will be made in the years to come.

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