TESPAR paves the way for Smart Sensors

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A new emerging market

A cheap smart sensor that interprets sounds, noises and vibration is a compelling concept. It might provide early warning of potential failure conditions and other significant events, or even recognise command words, or the individuals authorised to use a particular service or piece of equipment. For most applications, such devices demand the processing of complex signal data into a “metric” or “signature” form that can be compared against templates or archetypes representative of conditions to be recognised.

In these tasks, classical Fourier-based methods are proving inadequate in several key practical respects. Producing a satisfactory metric requires a considerable amount of Digital Signal Processing (DSP) power, a feature incompatible with goals of low cost, low power demand and minimum silicon real estate. Furthermore, processing regimes in the frequency domain that permit the effective exploitation of the classification power of Fast Artificial Neural Networks (FANNs) and Hidden Markov Models (HMMs) are subject to complexities such as dynamic time warping, and to impulsive noise artefacts which spread across the whole frequency spectrum.

A novel time domain approach to signal processing and recognition is now opening up the Smart Sensor concept, creating new markets where there is a growing and as yet unsatisfied appetite. Smart Sensors, new generation Smart Cards, intelligent Security Systems, time- and money- saving Diagnostic Instruments, low-cost Speech Response devices and Biometric Verification systems are just a few examples of applications for Domain Dynamics’ TESPAR/FANN technology. Its power is exemplified in its ability to classify many signals that remain inseparable in the Frequency Domain.

TESPAR/FANN technology

TESPAR/FANN technology developed and patented by Domain Dynamics Limited now makes automatic recognition and classification devices such as Smart Sensors technically and commercially feasible. TESPAR/FANN methods provide a new digital data / neural network combination which is proving highly effective in all kinds of automatic signal recognition applications. TESPAR/FANN involves the integration of novel *Time Encoded Signal Processing And Recognition* (TESPAR) waveform coding procedures with orthogonal *Fast Artificial Neural Networks* (FANNs) in purpose-designed structures that permit highly flexible decision making / data fusion hierarchies to be tailored to match the needs of the recognition or classification task, however simple or complex.

TESPAR coding

TESPAR is a new simplified digital language, first proposed by King and Gosling [1] for coding speech. The process is equally valid for any band-limited waveform from, for example seismic signals with frequencies and bandwidths of fractions of a hertz, to radio frequency signals in the gigaHertz region, and beyond.

TESPAR is based on a precise mathematical description of waveforms, involving polynomial theory, which shows how a signal of finite bandwidth (“band-limited”) can be completely described in terms of the locations of its real and complex zeros. This contrasts with the more conventional approach of linear transformations based on “amplitude” sampling at regular intervals, described by Fourier, Nyquist, Shannon and others. The real and complex zero descriptors of TESPAR and the time-bandwidth data produced by a Fourier transform are mathematically equivalent, both resulting in 2TW (the Shannon Number) digital sample data points describing the waveform [2]. Mathematical background to this zero-based approach is outlined in Voelcker [3] and Requicha [4].

Given the real and complex zero locations of the signal, a vector quantisation procedure has been deployed to code these data into a small series of discrete numerical descriptors, typically around 30 (the TESPAR *symbol alphabet*). Holbeche [5] gives an account of one version of this coding. TESPAR coders can be implemented in hardware or software, and produce a stream of numerical symbols (from the alphabet set) which naturally follow the input waveform in the time domain.

Matrix formation

The output from a TESPAR coder may be converted into a variety of progressively informative matrix data structures. For example, the single-dimension vector (or *S-matrix*) is a histogram recording the frequency with which each TESPAR coded symbol occurs in the data stream. A more discriminating data set is the two-dimensional histogram or *A-matrix* which is formed from the frequency of symbol pairs. Extending this to 3 dimensions would improve the discrimination power still further. Figures 1 and 2 show typical A and S matrices.

Various coding strategies are available to make best use of information provided by waveform amplitude, duration or shape descriptors, and by introducing the idea of 'lag' (i.e. taking non-adjacent pairs) into matrix formation, to exclude or emphasise artefacts that recur at particular rates.

A very great deal of flexibility is available in the creation of TESPAR matrices, offering the designer powerful methods of tailoring the metric to the special demands of the application.

Classification

A further very important outcome of the matrix formation technique is that the TESPAR data structures are of fixed size, dependent upon the alphabet used. This makes for regimes of processing that are both stable and simple to implement. In a typical classification task, TESPAR matrices for several samples of known operational conditions or events may be collected, and used to produce a reference matrix or *archetype* which embodies the unique characteristics of that event.

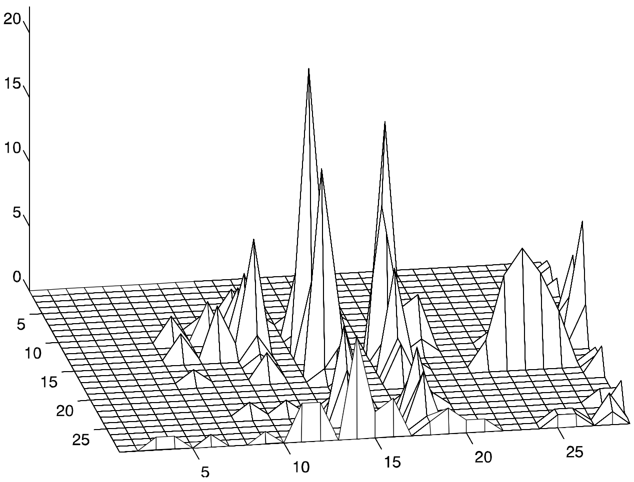

Figure 1 Typical un-normalised TESPAR A-matrix

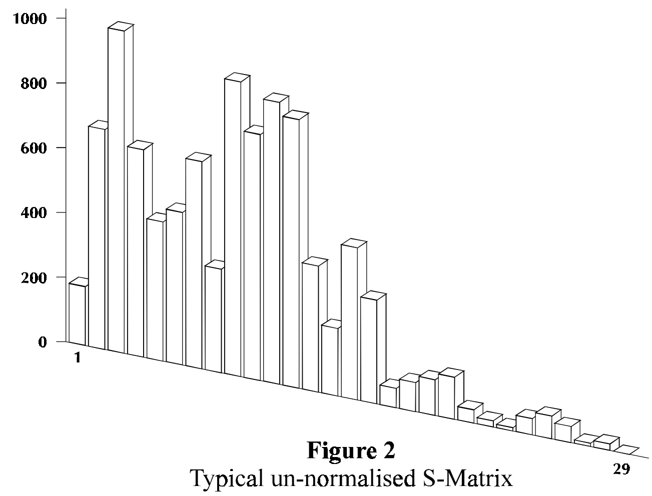

Figure 2
Typical un-normalised S-Matrix

Subsequently during live monitoring, new matrices are created in situ and continuously compared against the trained archetypes for a classification judgement to be made. All standard statistical methods, such as angular correlation, can be applied in the decision making process, and yield useful results.

The Artificial Neural Network dimension

Potentially far more powerful is the possibility of applying Artificial Neural Network methods of pattern classification to the TESPAR matrices. Because TESPAR matrices are of fixed size and dimension, they are ideally matched to the input requirements of Neural Networks. Recent practical experience [6] confirms that the TESPAR/FANN combination enables the introduction of very powerful classification procedures, producing system performances previously considered infeasible, and including an ability to separate many signals that remain indistinguishable in the frequency domain.

Performance advantages

In many important practical respects, TESPAR-based classification techniques show significant performance advantages over conventional Fourier based methods. For example:

- computer processing power demand is typically 2 orders of magnitude less, with consequent lower power consumption.
- the simple data structures are both compact and of fixed dimension, such that limited processing and memory resources are no barrier to efficient implementation. This has important benefits for data storage and communication operations, as TESPAR coding provides a very efficient data reduction method.
- the data structures offer very high degrees of discrimination, and are optimally matched for classification using FANN architectures.
- input can be obtained from low cost sensors. In many applications, classification results indistinguishable from those obtained using the high cost alternatives (whose linearity is often essential when using frequency domain signal analysis methods) have been obtained.
- for many real world applications, false alarm and other system errors can, by routine system design, be made vanishingly small.
- classification speed is minimal, e.g. less than 1 second using current popular microprocessor technology for a single pass classification.

Smart Sensor issues

The Smart Sensor concept combines a sensor and electronic processing device to give local and immediate condition classification without the need for central computation. Well established advances in silicon technology permit both elements to be integrated on the same substrate. For such devices to be viable, the availability of cheap, simple and appropriate processing capabilities, with embodiments suited to both high and low levels of production volume, is crucial. The processor core needs no sophisticated DSP capability, and could be a readily available 8-bit microcontroller.

Smart Sensors offer the key benefit of keeping information transfer rates from the component being monitored to the monitoring system to an absolute minimum. In the simplest case, just a single bit state change from 0 to 1 provides the “good” to “no good” condition warning. But TESPAR/FANN based Smart Sensors can classify several possible conditions.

For developers wanting to create Smart Sensors, the TESPAR coding and vector quantisation process is already available both as a software algorithm, and in a low power ASIC silicon design. Beyond this, TriTech Microelectronics of Singapore are in the process of producing a range of very low cost, low power TESPAR embodiments in silicon which offer a high degree of flexibility for integration into a wide range of potential high volume TESPAR applications.

In association with this activity, a collaboration with King’s College and University College London is now adapting their pRAM Neural Network architecture to the task of classifying TESPAR data structures [7, 8, 9]. pRAM technology provides Neural Networks that *can be trained on the silicon itself*. Thus the realisation of complete TESPAR/FANN low cost single chip Smart Sensor solutions is in sight, capable of training in situ and adaptable to widely differing applications of varying volume. This capability opens the interesting possibility of sensors that are not merely smart, but adaptive too.

Classifier Design strategies

In many Smart Sensor applications, single FANNs suitably trained may provide fully acceptable results. For more complex cases, the use of a multiple FANN architecture with the classification decision based on a data fusion / vote taking decision logic across the network set offers the possibility of making system errors vanishingly small by design. As an example, a typical speaker verification architecture (fig. 3) aimed at use in a Smart Card may consist of 15 or more networks, with practical system error performances moving towards the 1 in 100,000 target False Reject performance figure set as a “requirement” by the UK banking community for biometric verification methods [10].

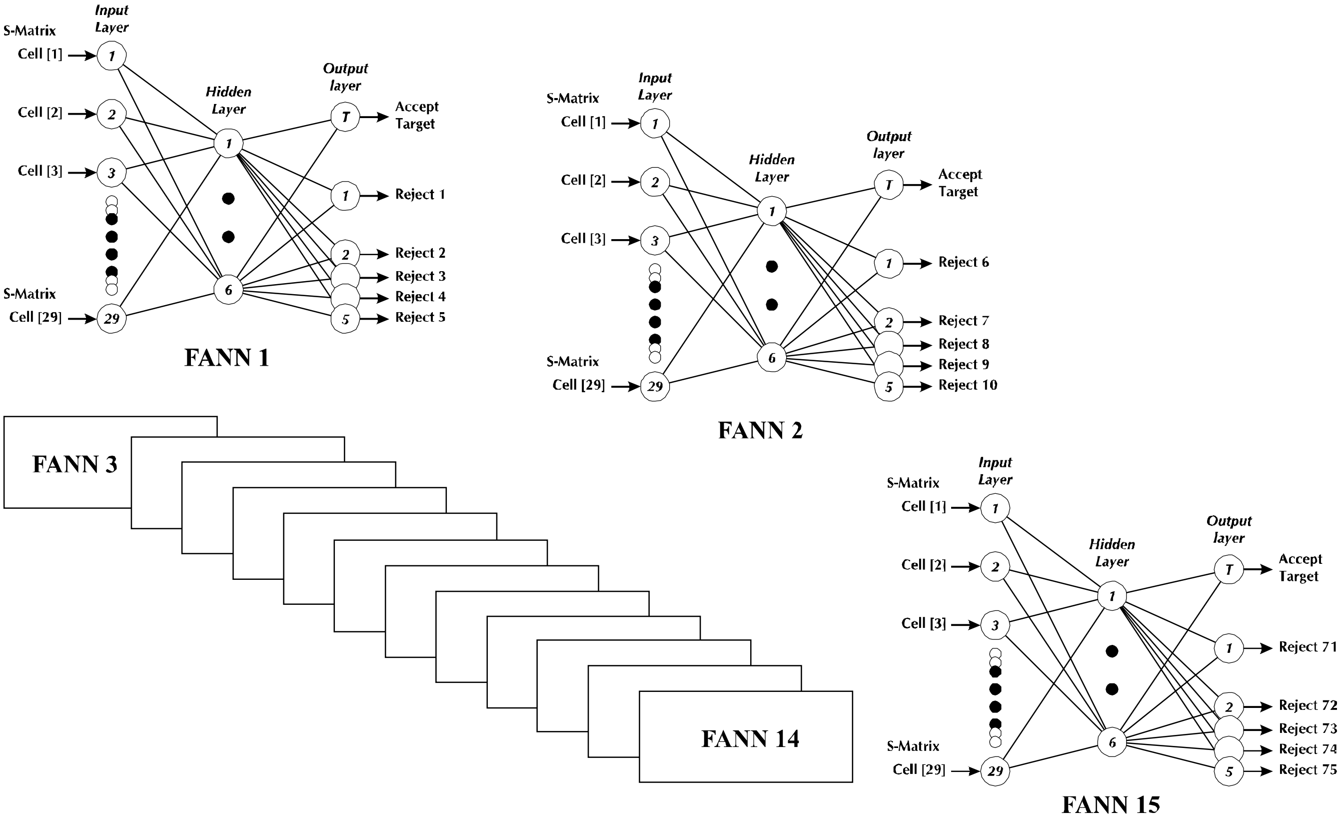

Fig. 3 - Typical Multiple Network Speaker Verification Architecture

Massively Parallel Network Architectures

The data needed to store a TESPAR/FANN classification architecture is already much smaller than many competitor methods. The latest work, however, is showing that alternative methods can capitalise on the strengths of the multiple network architecture, while not requiring the significant training procedures, and enabling all the describing information to be contained in as little as 50 or 60 eight-bit bytes of data, irrespective of the size, dimensionality and complexity of the input data matrices.

The new technique of Massively Parallel Network Architectures embodies the immense power of massively parallel networks and data fusion enhancements to achieve the performance associated with a large number N of trained networks, where N may be, for example, between 100 and 1500.

In this technique, an ordered set of N networks, all different, may be generated a priori in non-real time using input data from a large number of representative samples. The N networks are then used as an interrogation set, against which all signal samples are to be compared, both at registration (‘training’) and subsequent interrogation (classification).

When being registered against the N net interrogation set, a signal sample is first converted to appropriate TESPAR matrices, and compared against each of the N nets in turn. Each net will produce an output on one of its nodes, indicating to which of the pre-trained signals in the net the input sample was closest. By examining the pattern of data outputs from all N nets, a variety of strategies is available for characterising the signal. For example, using an ordered set of N=100 nets, a signal can be characterised by the corresponding data set of 100 three-bit words, i.e. circa 38 eight-bit bytes.

This new, patented technique has especial potential in Biometric Verification and Spoken Word Recognition - both very specialised Smart Sensors applications for identifying people or recognising a key vocabulary.

Development tools

All the work described has been conducted using a Domain Dynamics' proprietary PC-based development system, the TADS-XS 50. The system includes an extensive library of both conventional and TESPAR signal processing and data analysis software, operating under the popular MATLAB™ graphical user interface. FANN classification architectures are created, trained, tested and interrogated within the system using the proprietary FasTEST software suite. This development facility is proving extremely valuable in enabling third parties to evaluate TESPAR/FANN architectures in a wide range of real world sensor output classification tasks.

CASE STUDIES

Out of more than sixty real world case and feasibility studies to date conducted by Domain Dynamics for a variety of organisations, many applications offer intriguing and potentially profitable possibilities for the development of smart sensors:

- monitoring the particle size and state of ore granules en route through a series of crushing mills to the smelter
- "listening" to vibration from railway rolling stock axles to predict failure conditions
- portable instruments that make quick and accurate diagnosis of vehicle electric and engine management system faults
- intelligent security and intruder detection systems
- detecting sticking valves in diesel engines and compressors before they lead to a fault condition
- identifying and locating electrical faults in HV power transformers
- early warning of conditions that precede failure in helicopter drive gearboxes and rotors
- word recognition devices that perform well in noise

As a practical illustration of a TESPAR/FANN application, three operating conditions of high speed rotary reciprocating compressors are examined [11]. Two of the conditions may result in costly repair and downtime. Monitoring was carried out by recording noise signals via a simple acoustic sensor placed within a few centimetres of the compressor.

Previous investigations had shown that the three key conditions of interest were very difficult to separate using conventional frequency domain procedures (fig. 4).

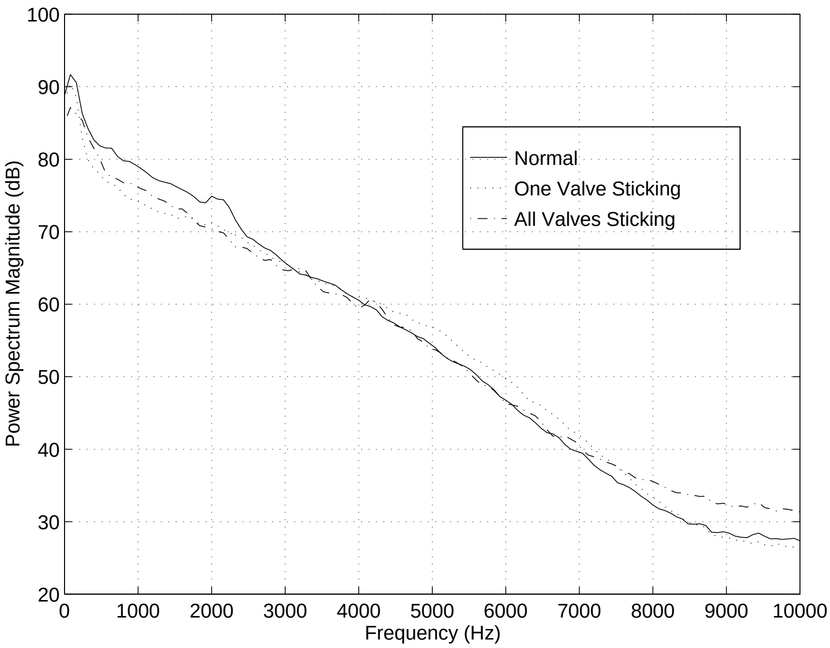

Fig. 4 - Superimposed Power Spectra for the 3 Compressor Conditions

Signal samples from the three conditions were encoded to TESPAR A-matrices and used to train an 841-10-3 floating point Artificial Neural Network. Random signal condition samples not used in the training process were then encoded to A-matrices and applied as input to the FANN. The condition output of the FANN produced the correct condition classification for every input signal in turn, with a worst case score of 0.824 and an average score of 0.970 across 30 interrogations.

A simple 3-output Smart Sensor placed on each compressor would provide an economic method of monitoring their performance. Unambiguous indications of developing fault conditions would be available, enabling maintenance before actual failure, and avoiding the current strategy of over-maintenance, which has not prevented every case of failure.

CONCLUSIONS

Experience to date with TESPAR/FANN hardware and software indicates:

1. The TESPAR/FANN combination is a powerful, robust, flexible and economic technology for a wide range of automatic classification and signal recognition applications.

2. TESPAR/FANN procedures permit system errors to be made vanishingly small over a wide range of real world applications.

3. New massively parallel network strategies permit essential classification embodiment data to be stored within a few tens of 8-bit bytes.

4. TESPAR/FANN hardware and software development tools are readily available for developing real world Smart Sensor applications in a cost-effective way.

5. On-going developments will enable low cost smart sensors to be realised via trainable TESPAR/FANN classifiers integrated with a sensor on silicon.

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