Many techniques are available for the estimation of the power spectrum of a stationary random process. While power spectrum estimation is a problem which falls within the domain of signal processing, the problem of inferring information falls within the domain of artificial intelligence (AI). With a wide variety of different types of power spectrum estimation techniques to choose from, an equally wide range of differing spectral estimates may be produced. Each estimate, however, may be used to infer information about the time series. By defining an appropriate knowledge base, a system is being developed to infer information from power spectrum estimates. This system combines the estimates produced by a variety of current spectrum estimation techniques in order to formulate a composite spectral estimate.
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INTRODUCTION

The integration of signal processing with artificial intelligence (AI) is not a new idea. In fact, the merger of both of these disciplines is proving useful in applications where the goal is the symbolic description of a signal or the extraction and recognition of signal features. Systems which presently apply artificial intelligence to signal processing include EARSAY-II [1], SIAP [2], and the dipmeter advisor [3]. In this paper, we describe some preliminary work on the development of a system which applies AI techniques to the problem of estimating the power spectrum of a stationary random process. In particular, the general philosophy and structure of a Knowledge-Based Spectral Estimation (K-BASE) program is overviewed.

Although many signal processing techniques have been developed for estimating the power spectrum of a stationary random process, each produces a different estimate of the power spectrum [4]. While these estimates may be quite different, each sheds light on the underlying characteristics of the random process and provides useful information about the true power spectrum. The goal of our K-BASE program is to extract the relevant pieces of information from each of these estimates to form a composite description of the power spectrum. Thus, for any given spectrum estimation technique, the underlying assumptions concerning the signal generation process, the inherent strengths and limitations of the technique, and the signal features or model parameters produced by the technique are viewed as the knowledge. Collecting these pieces of knowledge together, a knowledge base is produced which forms the foundation for the K-BASE program. A control strategy is used to guide the search through the space of possible solutions. The information in the knowledge base is used to make inferences and deductions about the true power spectrum. Such a system, therefore, is able to draw upon the strengths of each of the power spectrum estimation techniques to derive a spectral estimate in a data-adaptive and "intelligent" manner. With this knowledge base and control structure it is also possible to make inferences and apply various signal processing techniques to test the validity of these inferences.

In the following sections, we overview the structure of the K-BASE program. First, we describe the contents of the knowledge base which is divided into four knowledge domains and provides the "intelligence" of the K-BASE system. Then we describe the control strategy which draws upon the knowledge base to direct the search through the problem space to reach the desired goal of the program, i.e., the description of the power spectrum. Finally, we describe a prototype system being developed which focuses on a problem of limited scope by restricting the size of the knowledge base.

K-BASE PROGRAM

We are currently in the preliminary stages of developing a Knowledge-Based Spectral Estimation (K-BASE) system. The purpose of this program is to develop a prototype system to find the power spectrum by using information gained from a set of spectral estimation techniques.

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The key components of the K-BASE program are the knowledge domains required for spectral estimation, the control strategies for reaching the final goal and the methods used to determine when the final goal is reached, and a representation of the knowledge. Due to the large amount of information available on power spectrum estimation, the prototype program is being developed using a subset of the available spectral estimation techniques. As with other knowledge-base systems (primarily expert systems) performance deteriorates when the signal analyzed falls outside the scope of the knowledge-base [3]. Therefore, the development of the K-BASE system will be a continual process with the knowledge base being expanded with each version of the program.

Knowledge Domains

The first step in the development of the K-BASE program is the specification of the knowledge base. Preliminary studies indicate that there are four general knowledge domains to be considered in the development of the knowledge base. These domains include:

- The knowledge domain associated with the spectrum estimation techniques,
- The data models and the a priori information associated with the generation of the time series,
- The signal-to-symbol transformation, and
- Signal processing and signal manipulation techniques

The knowledge domain of the spectrum estimation techniques includes a variety of different types of information. At the highest level within this domain is a list of the various power spectrum estimation techniques, i.e., the estimation tools used in deriving information for making inferences and deductions about the time series structure. For each of these techniques there is a catalogue of information which specifies the characteristics, behavior, and limitations about the estimate produced by the technique. For example, it will be important to specify the ways in which a spectrum estimate is affected by variations of such parameters as the order of an AR or ARMA model, the time series record length, the number of autocorrelation lags, and the type of spectral or data record window. Another important piece of knowledge includes the strengths and limitations of the spectral estimation technique. Included in this area would be information concerning the data types for which the technique is best suited.

The maximum entropy method (MEM), for example, performs very well for time series which may be accurately modelled as an AR process. Pisarenko's method, on the other hand, works very well for pure tones (sinusoids) in white noise. Equally important is information concerning the performance of the technique when it operates on data which does not fit the assumed model as well as lists of potential problems associated with a given technique operating under certain classes of signal. For example, it will be important to know for what types of signals and with what types of spectral estimation techniques line splitting is expected to be more pronounced. As another example, it will be important to know when a spectrum estimation procedure produces biased estimates of spectral peaks. In other words, the knowledge domain associated with the power spectrum estimation techniques is accomplished by an exhaustive catalogue of information and facts about each estimation procedure.

The second domain of knowledge concerns information about the signal which is being analyzed. Within this domain falls such information as the data model and a priori information associated with the generation of the time series. The physics of wave propagation within geological formations, for example, provides information about seismic time series records. The theory of speech production, on the other hand, provides useful models which may be used in describing the time series representing speech waveforms.

The third knowledge domain, which traditionally is not usually considered to be a part of a knowledge base, is a signal-to-symbol transformation [3]. This signal-to-symbol transformation provides a convenient means for storing and manipulating conceptually inferred information about a signal or its estimated spectrum. Signal-to-symbol transformations are accomplished by a grammar which parses the time series [6] and can lead to representations of the form:

**INTRODUCTION**

<table>
<thead>
<tr>
<th>INTERVAL</th>
<th>SYMBOLIC REPRESENTATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>10kHz to 20kHz</td>
<td>FLOOR-&gt;CUSBP-&gt;RISE-&gt;CAP-&gt;RAMP</td>
</tr>
</tbody>
</table>

This symbolic representation may have a quantitative description associated with each symbol such as the level of the floor, the slope of a rise or a ramp, the minimum value of a cusp, or the area under a cap [7]. The primary reason for including this signal grammar in the knowledge base is to allow for the possibility of incorporating knowledge about how the grammar is structured, how it is designed, and what its characteristics and features are.

The last knowledge domain contains the signal processing and the signal manipulation techniques. These techniques include such operations as filtering, windowing, and the removal of sinusoids. They are intended to be used as additional tools to further enhance a signal or its spectrum estimate to test various hypotheses. More specifically, after an initial analysis is performed, a set of hypotheses are made. Following this analysis, other techniques may be invoked in order to help confirm or disprove these hypotheses, thus increasing the confidence of inferences. For example, it has been recently observed that for the cases in which
two closely spaced spectral peaks are not resolv-
ed by a high resolution spectral estimation
technique such as MMSE, the peaks may often be
resolved by placing zeros in the spectrum
(usually in an adaptive fashion) [8]. Zero
insertion, therefore, is viewed as a potentially
useful tool for confirming the existence of
multiple smeared peaks or for checking for the
possibility of spectral line splitting. For each
signal processing technique considered, knowledge
about its properties, limitations, and desired
goals needs to be identified.

The development of a total system to handle
types of spectrum estimation techniques,
various types of signals, many signal parsing
grammars, and general signal processing techni-
ques is a formidable task. Thus, the knowledge
base to be initially developed will be limited in
scope. Concentration is being focused on a
small number of spectral estimation techniques
and attention is being directed towards a specifi-
class of signals. However, as the knowledge
base evolves, other information in the form of
additional power spectrum estimation techniques
and signal classes will be incorporated.

Control Strategy

The control strategy provides the mechanism
to progress from the initial state (unknown
signal) to the goal state (signal description).
It directs the search through the problem
space. The initial state is the sequence of
samples, and the goal state might be:

Two sinusoids in white noise at
frequencies 10kHz and 20kHz with
equal power; signal-to-noise ratio
4dB.

Since the desired output of a spectrum esti-
mation program is typically answers to questions
such as "are there one or two sinusoids," the
control structure uses a goal-directed or forward
chaining control strategy to generate a set of
initial hypotheses [9]. Based on this initial
set of hypotheses, additional signal processing
and signal analysis is performed to evaluate the
probability of each hypothesis. For example, if
the initial pass deduces that either one or two
sinusoids are present in the time series, then the
controller analyses the data record in the
context of this hypothesis. The second pass uses
a mixed strategy (e.g. means-ends analysis) to
determine the characteristics of the sinusoids
and the confidence level of the analysis.

Knowledge Representation

In the K-BASE system, different types of
knowledge are used in the knowledge base. There
is the signal-to-symbol transformer, the rela-
tional information associated with the spectral
estimation techniques and their properties, and
the rules for how, when, and what to extract from
each power spectrum estimate generated. There
are a number of different ways of representing
knowledge. Two common methods are the use of
production rules and the use of semantic
frames. In K-BASE, both of these forms are used
in knowledge representation. For example, since
the knowledge about how to use the set of spec-
tral estimation techniques is in the form of
rules, production rules are used. Knowledge
about the properties and limitations of a given
power spectrum estimation technique, on the other
hand, is easier to represent in terms of condi-
tions. Semantic frames provide a convenient
mechanism for representing this relational know-
ledge. The symbolic representation of the power
spectrum estimate is also in a relational
(sequential) form and is therefore also easily
represented in the form of semantic frames.

Subset of Knowledge

The development of a knowledge-based power
spectrum estimation system which includes all
estimation techniques is impractical as an
initial attempt. The first prototype system, there-
fore, concentrates on a selected number of
spectral estimation techniques. In the K-BASE
program, the spectral estimation techniques
chosen are the periodogram, the maximum entropy
method (MEM), and Pisarenko's method. These
methods were selected since they produce very
different spectrum estimates.

In addition to constraining the spectrum
estimation methods used in the K-BASE program,
the types of signals and classes of signals are con-
sidered. Specifically, the program focuses its attention
on relatively low order (N ≤ 4) AR processes to
which sinusoids have been added.

A promising technique, zero insertion [8],
will also be included as a technique to analyze
signals. This technique is not a spectrum esti-
mation technique, but a method to process the
signal to resolve ambiguity. It relies on an
initial hypothesis of the characteristics of the
signal to do. These type of signal manipula-
tion techniques should be of great use in an AR
system to accomplish spectral estimation.

The development of the K-BASE program on a
subset of the spectral estimation knowledge-base
will not be as powerful as using all spectral
estimation techniques, for all signal types, with
all signal modification procedures. It is hoped that
the subset knowledge-base will demonstrate
feasibility and prove useful for the class of
problems for which its knowledge covers. The
development of a knowledge-base is an on-
going process of development-test-upgrade. It is
anticipated that other areas of knowledge may be
included in later versions.

CONCLUSIONS

The K-BASE program's goal is to automate the
analysis of the power spectrum based on estimates
generated by a variety of techniques. To infer information about the true power spectrum from a
variety of PEE techniques requires the use of
to knowledge. An artificial intelligence approach
appears to be suited to this problem.

The knowledge base is composed of four major
parts: the signal-to-symbol transformer, the
spectral estimation techniques, the type of
signals, and the signal manipulation
techniques. A control strategy directs the
search for the desired goal state (description of
the true power spectrum). The strategy is to
reason forward to a set of hypotheses, then use a
mixed strategy to determine a more detailed
analysis with confidence factors. The initial
knowledge base is limited in scope to a few
spectral estimation techniques and for a specific
signal generation model. This will form the
foundation for further extensions of the
knowledge base.

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