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Joint detection and estimation theory in underwater acoustics signal processing

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1. Introduction

Many statistical decision problems in engineering applications fall into one of two categories: *detection* and *estimation*. In the detection problem, the objective is to decide if there is a signal in the observation subject to a constraint of false alarm. In the estimation problem a signal which is known to be present in the observations has an unknown feature represented by a parameter, and the objective is to decide on the parameter value. Past work, for the most part, has treated the reception processes of signal detection and signal estimation as separate and distinct operations. However, one frequently encounters applications where estimation has to be performed under uncertainty of signal presence. Only recently have reception schemes been considered where the two operations are interrelated and performed jointly. Many of the results can be applied to data processing procedures and applications have been made to sonar, radar, and communications and so on. The associated decision problem is called *simultaneous or joint detection and estimation*.

2. Formulation of joint detection and estimation

Middleton and Esposito [1] were the first to study simultaneous detection and estimation (D/E) within the framework of statistical decision theory. They obtained jointly optimum Bayes detector and estimation structures for binary on-off reception in a single observation interval. Also, the notion of coupling between the two operations of detection and estimation was introduced and various coupling schemes were discussed. The optimum simultaneous detection and estimation is treated within the framework of general Bayes decision theory, and the coupling strategies between the detection and estimation processes were considered. Recent investigations in the general area of simultaneous detection and estimation include works by Lainiotis [2], Birdsall, Gobien [3], Baygun [4] and Wax [5,6] and so on.

Lainiotis extended the results of Middleton to the single-shot continuous data case and generalized to joint Bayesian detection-estimation-system identification. By utilizing the adaptive approach, closed form integral expressions are given. Signal random process is assumed to be modeled by the state-variable model. Baygun and Alfred develop a multihypothesis testing framework for studying the tradeoffs between detection and parameter estimation (classification) for a finite discrete parameter set. They present a min-max method which form an important solution category because they ensure optimal detector or estimator performance under worst case conditions. Min-max methods have been applied to problems of adaptive array processing and MFP. Wax and Kailath present a novel approach to the problem that is based on the application of the information theoretic criteria for model selection introduced by Akaike (AIC) and by Achwartz and Rissanen (MDL), the number of signals is determined as the value for which the AIC and the MDL criteria is minimized.

In the simultaneous detection and estimation problem for the case where the signal evolves as a Gauss Markov process and is observed in white Gaussian noise. The optimal causal estimator and detector structures are obtained explicitly for quadratic cost functions. It is shown that the estimate and the detection test statistic can be computed on-line sequentially and that the optimal receiver for this joint detection-estimation problem is readily synthesized. Generally, the quadratic cost functions are difficult to find or not exist. In the theory of statistical, the class of estimation problems can be restricted to those which admit a sufficient statistic of the observation for the unknown parameter. In other words, there exists a statistic of the observation which has fixed dimension regardless of the number of observation and contains as much information about unknown parameter as observations themselves. Birdsall [3] also introduced the concept of a reproducing density function. Choosing *a priori* probability density function arbitrary, and with the observations be processed recursively the *a posteriori* will closed enough to the true value. So we can exchange of information between the detection and the estimation blocks, and use this information to narrow the pdfs of the parameters around the estimated values. If we adapt the joint signal detection and parameter estimation schemes, so as to reduce the statistic uncertainty due to the parameters themselves step by step, the performance of detection and estimation can be significantly improved.

3. Joint detection and estimation of a plane wave known except for direction

The estimation of the direction of arrival (DOA) of a known signal is a central problem in many fields including radar, sonar, and communication. Radar and sonar systems are based on transmitting a known signal and estimating DOA of

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the reflected signal. Unfortunately, in many cases, the reflected signal is not composed of a single reflection but rather from multiple reflections having different DOA's. Generally, the number of signal impinging on the array is unknown. Wax [5] present a novel approach to the problem of detecting the number and estimating the direction of signals simultaneously, based on MDL principle which considers the partition of the received vector into its components in the signal and noise subspaces. A fast computational method of the AP algorithm which is convenient for the simulation of computer was given by Wang [7].

Wang also investigated the problem of the detection performance of two candidate receiver structure for a plane wave known except for direction (SKED). Included are the Bayes optimal detector and an estimate and plug structure.

We present a novel approach to the problem of detecting the number and estimating the direction of sources impinging on a passive sensor array simultaneously, based on MDL principle which considers the partition of the received vector into its components in the signal and noise subspaces. A fast computational method of the AP algorithm which is convenient for the simulation of computer is given. Simulation results show that performance degradation from optimal for the estimate and plug structure considered is significant. Even though a "good" estimation has been coupled with the parameters known detector, performance in the global sense has suffered. The reason is that the *a priori* knowledge of the parameters is not properly incorporating into the processor design. In fact, the conventional array processor do have an estimate and plug structure.

4. Application of joint detection and estimation in MFP

Matched field processing (MFP) has been receiving increased attention in recent years. Originally, MFP was intended as a source localization technique. As originally conceived, the MFP concept was posed as an estimation problem. That is, it was proposed as a method to determine the range, depth, and bearing of an acoustic source in the ocean. That is, the *a priori* probability of the source signal's presence, $p(\mathrm{H}_1)$, is unity. However, if the source location is not known *a priori* and $p(\mathrm{H}_1)$ is known to be less than unity, then a series of detection decisions over an exhaustive set of source coordinates constitutes a detection procedure where the results incidently provide an estimation of source location. Another difficult problem in MFP is the mismatch. Mismatch occurs mainly due to errors in the sound velocity profile, water depth, bottom parameters, surface condition, and hydrophone positions. This problem can be solved if those parameters be estimated correctly. So MFP requires joint detection-estimation procedures [8].

An alternate approach to the problem is found in the more recent work of Candy and Sullivan [9], who formulate the problem using a spatial state-space approach. The advantage of this is that it allows the structure to be extended to a Gauss-Markov noise process with additive Gaussian noise. This approach can include uncertainties in the model represented now as dynamical system noise and measurement noise by eigenvalue equation and state equation. The model-based signal processing is concerned with the incorporation of environmental (propagation, seabed, sound speed, etc.), measurement (sensor arrays) and noise (ambient, shipping, surface, etc.) models along capable of detecting, filtering (estimating) and localizing an acoustic source (target) in the complex ocean environment. It can enhance signal-to-noise ratio by sequentially estimating both modes and fields by means of a Kalman filter formulation. Furthermore, the resulting residuals or so-called innovation sequence then allows the model to be continuously monitored and updated. In addition, this state space formulation provides a framework for sequential detection for the case where $p(\mathrm{H}_1) < 1$.

The possibility of applying the method of joint D/E to the problem of MFP was investigated in [7]. A model-based signal processing was investigated in detail, and two methods of joint D/E which can be applied to MFP were given.

5. Conclusions

In this paper, the analysis of the joint detection and estimation scheme in underwater acoustics signal processing has been carried out. The theories of joint D/E are summarized. In particular, the possibility of applying the method of joint D/E to the problem of DOA and MFP was investigated particularly.

In conclusion, it has been shown that the joint schemes can achieve optimum performance given a certain amount of a priori information. In fact, the separation schemes induced by the use of discrete random parameters as for the detection task do not permit an improvement of the average performance with respect to joint schemes. In other words, if we adapt the joint signal detection and estimation schemes, so as to reduce the statistic uncertainty due to the parameters themselves step by step, the performance of detection and estimation can be significantly improved. In order to improve the performance of such schemes, it is therefore necessary to find a way to refine the statistical information about the unknown parameters. Some developments of the matter are addressed in [10], where a closed-loop scheme for modal analysis is proposed which allows the detector to benefit from additional information yielded by the estimator. However, several problems remain still unsolved. Whether a general formulation of joint detection and estimation exists or not in any term and how much it can improve the performance in underwater acoustics signal processing is unknown.

References

[1] D. Middleton and R. Esposito, "Simultaneous optimum detection and estimation of signal in noise," *IEEE*, **IT-14**, 434–444 (1968).

[2] D. G. Lainiotis, "On a gneral relationship between estimation, detection and the Bhattacharya coefficient," *IEEE*, **IT-15**, 548–556 (1970).

[3] T. G. Birdsall and J. O. Gobien, "Sufficient statistics and reproducing densities in simultaneous sequential detection and estimation," *IEEE*, **IT-19**, 760–768 (1973).

[4] B. Baygun and A. O. Hero, "Optimal simultaneous detection and estimation under a false alarm constraint," *IEEE*, **IT-41**, 688–703 (1995).

[5] M. Wax and I. Ziskind, "Detection of the number of coherent signals by the MDL principle," *IEEE ASSP*, **37**, 1190–1196 (1989).

[6] I. Ziskind and M. Wax, "Maximum likelihood localization of

multiple sources by alternating projection," *IEEE ASSP*, **36**, 1553–1560 (1988).
[7] L. J. Wang, "Application research of joint detection and estimation theory in underwater acoustics signal processing," *M.Sc Dissertation, Naval Univ. of Eng., Nanjing* (2002).
[8] E. J. Sullivan and D. Middleton, "Estimation and detection issues in matched-field processing," *IEEE J. Oceanic Eng.*, **18**, 156–167 (1993).
[9] J. V. Candy, *Signal Processing: The Model-based Approach* (McGrawHill, New York, 1986).
[10] E. Magli, G. Olmo and L. Lo Presti, "Joint statistical signal detection and estimation. Part II: A high-performance closed-loop technique," *Signal Process.*, **80**, 773–786 (2000).
[11] W. S. Hodgkiss, "Optimal array processor performance trade-offs under directional uncertainty," *IEEE*, **AES-12**, 605–615 (1976).
[12] D. G. Lainiotis, "On a gneral relationship between estimation, detection and the Bhattacharya coefficient," *IEEE*, **IT-15**, 504–505 (1969).
[13] A. Fredriksen, D. S. O. Middleton and V. D. Vande Linde, "Simultaneous signal detection and estimation under multiple hypotheses," *IEEE*, **IT-18**, 106–110 (1972).
[14] A. G. Jaffer and S. C. Gupta, "Coupled detection-estimation of Gaussian processes in Gaussian noise," *IEEE*, **IT-18**, 106–110 (1972).
[15] L. E. Miller, "Muti-platform detection study," *AD-A073560*, Aug. (1979).
[16] M. Wax and T. Kailath, "Detection of signals by information theoretic criteria," *IEEE ASSP*, **33**, 387–392 (1985).