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IISc THESES ABSTRACTS

Thesis Abstract (Ph.D.)

Petri net-based techniques for modelling, analysis, and performance evaluation by Y. Narahari.
Research supervisor: N. Viswanadham.
Department: Computer Science and Automation.

1. Introduction

Modelling, analysis, and performance evaluation constitute an important aspect of the design and operation of distributed processing systems. In this context, Petri nets and their extensions have emerged as graphical modelling tools of significant practical value[1,2]. The research work reported in this thesis is concerned with the development of Petri net-based techniques for the modelling, analysis, and performance evaluation of distributed processing systems. As the application areas of our techniques, we focus on flexible manufacturing systems (FMSs)[3] and multiprocessors[4], which represent two important areas of current interest.

In the area of FMSs, we propose techniques, all based on nets, for modelling, logical analysis, and quantitative performance evaluation. For modelling and logical analysis, we employ classical Petri nets[1,2] and coloured Petri nets (CPNs)[5]. For performance evaluation, we use generalized stochastic Petri nets (GSPNs)[4,6] and Petri nets with deterministic and stochastic firing times (DSPNs)[7]. In the area of multiprocessors, we consider the performance evaluation of a fault-tolerant multiprocessor, FTMP, used in real-time air-traffic control aplications, using GSPNs and DSPNs. The investigations carried out in this thesis have significant potential in the design and operation of other classes of distributed systems as well.

2. Analytical contributions

The main analytical results of this thesis and their significance are presented below.

(i) A useful paradigm, called the union of Petri nets, is proposed to facilitate a systematic bottom up construction of Petri net models of FMSs. A coloured Petri-net model also can be obtained in a similar way using the concept of union of coloured Petri nets. The idea is to view the overall Petri-net model of an FMS as the union of the Petri-net models of the individual operations or subsystems of the FMS. This hierarchical philosophy of model construction is followed throughout the thesis to obtain Petri net or coloured Petri net models of FMSs. The resulting models could be used in conducting a logical analysis of the FMS or in designing efficient data structures and algorithms for the FMS simulation.

(ii) The second contribution of this thesis is in the computation of invariants of Petri nets and coloured Petri nets using the concept of net union. We develop a method of computing the invariants

of the union of Petri nets/coloured Petri nets in terms of the invariants of the individual nets and *vice versa*, under certain conditions. These results are immediately applicable in the process of hierarchical construction of net models of FMSs. The computed invariants can be used in verifying/investigating several important properties such as finiteness of resources/buffers, existence/absence of deadlocks, and specification errors.

(iii) The GSPN models of flexible manufacturing systems can be refined by using DSPN models which allow deterministic firing times in addition to exponentially distributed firing times. These DSPN models, however, will have concurrently enabled deterministic transitions and as a result, the existing analysis methods for DSPNs are not applicable. We obtain a set of sufficient conditions under which a DSPN model can be analyzed using the powerful regenerative simulation technique. We argue that the DSPN models of our interest satisfy the above conditions and can therefore be analyzed using regenerative simulation to obtain more accurate and realistic performance estimates than in the case of the GSPN models.

3. Applications

The analytical results obtained in this thesis have found use in three major applications: (i) deadlock investigation in a real-life FMS, (ii) performance modelling of FMSs, and (iii) performance evaluation of a fault-tolerant multiprocessor. These applications are presented below.

(i) Deadlocks represent a highly undesirable phenomenon in resource sharing systems and their importance in the context of FMSs has been recognized only recently. A major contribution of this thesis is in investigating the existence/absence of deadlocks in a given FMS, using the invariants of a net model of the FMS. As a significant practical illustration of this, we construct a Petri net model of a real-life FMS, the General Electric FMS, at Erie, Pennsylvania, USA, in a hierarchical way and formally prove the existence of several types of deadlocks in this system. We also suggest strategies to prevent/avoid these deadlocks. As a complementary example, we consider a three-stage automated transfer line and prove that there can exist no deadlocks in this system under the assumed operating conditions.

(ii) Quantitative performance evaluation is an essential part of the design and operation of FMSs[8]. As a new application of GSPNs, we show that GSPNs provide an effective modelling and performance evaluation tool for FMSs. We demonstrate the advantages of GSPNs by constructing and analyzing GSPN models of four illustrative manufacturing systems—a three stage automated transfer line, a manufacturing cell with material handling robots, a simple FMS with three machines and two part types, and the General Electric FMS. The analysis is carried out using a software package developed by us, for solving GSPN models. DSPN models are also considered.

(iii) FTMP (fault-tolerant multiprocessor) is an ultra-reliable real-time multiprocessor used in air traffic control applications. A study of the performance and reliability of the FTMP system assumes vital importance in view of its critical application. A closed queueing network model of FTMP, developed in the literature, has been refined by us using GSPN and DSPN models. We show how GSPNs and DSPNs adequately capture several architectural and operational features of the FTMP system, not modelled by the closed queueing network. Specifically, we model the individual behaviour of the job classes, priorities for using the system bus, and degradable performance due to processor failures.

References

1. PETERSON, J. L. — *Petri net theory and the modelling of systems*, 1981, Prentice-Hall.
2. REISIG, W. — *Petri nets: An Introduction*, EATCS monographs on theoretical computer science, 1985, Springer-Verlag.
3. — *Flexible manufacturing systems handbook*, 1983, Charles Stark Draper Laboratory, Inc., Cambridge, Massachusetts, USA.
4. MARSAN, M. A., BALBO, G. AND CONTE, G. — *Performance models of multiprocessor systems*, 1986, The MIT Press.
5. JENSEN, K. — Coloured Petri nets and the invariant method, *Theoretical Computer Sci.*, 1981, **14**, 317–336.
6. — *Proc. Inter. Workshop on timed Petri nets*, Torino, Italy, July 1985, IEEE Computer Society Press.
7. MARSAN, M. A. AND CHIOLA, G — On Petri nets with deterministic and exponential transition firing times, *Proc. VII Eur. Workshop on Petri nets*, Oxford, UK, July 1986, pp. 151–165.
8. SURI, R — An overview of evaluative models of flexible manufacturing systems, *Ann. Operations Res.*, 1985, **3**, 381–391.

Thesis Abstract (Ph.D.)

Multi-objective planning with performance scenarios—A goal programming approach by Usha Sridhar.
Research supervisor: B. G. Raghavendra.
Department: Management Studies.

1. Introduction

The planning problem in the firm typically involves multiple, often conflicting operational objectives which are to be met subject to given resource constraints. The choice of a course of action from among many possible alternatives in this multi-objective decision problem is a crucial managerial function. The size and complexity of the problem in practical situations has stimulated attempts to cast it in the form of a multi-objective decision making (MODM) model and obtain solutions with the use of mathematical tools[1,2]. All MODM techniques employ some form of preference information obtained from the decision maker (DM) to generate one or more solutions which are evaluated essentially on the basis of the associated levels of achievements of the objectives[3,4].

The expected levels of achievement of the objectives alone, however, do not convey to a DM adequate information on the achievable performance, as a consequence of a chosen plan. The choice of an alternative course of action is, therefore, difficult to make without the knowledge of the achievable performance, measured through a set of indicators as a performance 'scenario'.

Performance evaluation, which usually follows the implementation of a plan, involves a comparison of actual performance with a 'reference'. It is desirable, for the generation of internal control procedures, that the 'reference' be based on planned targets.

The problem of multi-objective planning and the analyses of performance scenarios are viewed in this thesis in an integrated manner in the framework of MODM models. From an evaluation of the various methods to solve the MODM problem[5-8], a new interactive methodology for effective planning with performance scenarios, based on goal programming (GP) technique, is developed. The methodology is based essentialy on two new algorithms that are concerned with the solution of GP models in such a manner that non-dominated solutions and the expected performance scenario are obtained. It also provides a 'reference' for performance evaluation.

2. A 'reference' for performance evaluation

The 'reference' is defined here to be that level of performance, beyond which no improvement is possible for the given priority ranking among the objectives. An algorithm to obtain this 'reference' performance from the GP model of the planning problem by sequentially 'stretching' the goals in accordance with the given priority ranking is developed. The algorithm produces a non-dominated solution to the problem. It is shown that if the set of performance indicators (PIs) chosen are known functions of the decision variables, then the performance achievable at this non-dominated solution can justifiably be called the 'best' and used as a form of 'reference' performance.

Briefly, the procedure employed to 'stretch' the goals is as follows. First the highest priority goal is made 'tougher' in every step of an iterative solution procedure, until any further increase in its set level leads to an under-achievement. The best achievable goal level is the 'stretched' level for this objective. In the next step the second highest priority goal is stretched in a similar way. Since the goal priorities are ordered lexicographically, the 'stretched' level for the second objective is that which cannot be exceeded maintaining the achievement of the first priority goal. This procedure is continued until all goals are 'stretched'.

The implicit trade-offs between goals is reflected in the changes in the performance scenario. It is shown that the analysis of the goal-performance relationship is possible through the use of the algorithm mentioned above. The sensitivity of the PIs to changes in the goal achievements provides crucial information which can be used for formulating managerial policies for better resource allocation and the determination of suitable goal-priority structures.

3. Generation of alternative performance scenarios

Given the 'reference' performance and the 'stretched' goal achievements, it is desirable to explore the solution space for other solutions which may also provide a satisfactory performance. The thesis addresses this problem of generating a set of alternative non-dominated solutions and associated performance scenarios in such a manner that the DM can obtain a wealth of information on the implicit trade-offs among the conflicting objectives and the PIs. A new methodology which permits this form of 'backward' computation from performance scenarios to goal achievements is developed. The core of the methodology is a new computational procedure built around the traditional GP formulation of the planning problem through which the analysis of the sensitivity of any chosen PI(s) or goals to changes in specific PIs is possible. The PIs are thus effectively used as 'instruments' to generate alternative non-dominated solutions.

The algorithm introduces the PIs one at a time as rigid constraints and obtains new solutions by setting their values to say, y% better than the 'reference' value. If a feasible solution exists, it must satisfy the constraint which rigidly fixes the value of a PI to the improved value. This constraint is met at the highest priority level and the goals are then met to their best extents possible in accordance with the other priorities set originally. It is guaranteed to be non-dominated since it is obtained by 'stretching' the goal levels.

By changing the value of y over a range in discrete steps, and obtaining the solutions the analyst can study the sensitivity of the goal achievements and performance scenarios to changes in the value of every PI. The thesis describes an algorithm to generate the trade-off information in the form of tables referred to as performance sensitivity tables (PST). The utility of a sensitivity analysis of this type is considerable in providing an insight into the latent trade-offs among goals for desired changes in PIs. The algorithm provides the goal levels that may be set to achieve a desired performance scenario, as against taking such information from the DM. Since it is possible for the analyst to generate PSTs for reasonable increments of all PI values, the DM need not make serious value judgements on goal achievements to search for alternative solutions. The PSTs thus enable him not only to understand the implicit trade-offs in the decision situation better, but also plan on the basis of a desired performance scenario.

This new methodology for planning lends itself well to the design of an interactive decision aid for planning. The design and software implementation of such a decision aid is described and sample screen menus illustrating its use are given.

4. Case studies

The applicability of the new methodologies to specific planning problems is demonstrated through the formulation, solution and detailed analyses of planning models developed for three real organizations. The organizations, chosen from both the manufacturing and service industry, differ in the type of ownership, business activity and managerial goals.

The first case is concerned with asset-liability management in a medium-sized public sector bank. The management of the bank desires the acheivement of three major objectives relating to the disbursement of advances to various sections of the society and the gross interest margin. The model takes account of the constraints imposed by the operating environment and the norms specified by the Government and the Reserve Bank of India.

The two other case studies deal with manufacturing organizations. These planning models seek to obtain a suitable product mix and reappropriation of profits towards dividends, retained earnings and employee welfare subject to demand and capacity constraints. The performance indicators used vary from financial ratios to a variety of indicators relating to the social objectives, often determined by government policies.

Results for the managements initial goal settings, the non-dominated solution, the 'best' performance and a number of PSTs are presented for each of the three cases. It is shown that the analyst can suggest several 'preferred regions of operations' on the basis of the goal trade-off information. The methodology is shown to be effective despite the diversity of operations of the organizations.

References

1. COHON, J. L. — *Multi-objective programming and planning*, 1978, Academic.
2. IJIRI, Y. — *Management goals and accounting for control*, 1965, Rand Mcnally, Chicago.
3. HWANG, C. L. *et al* — Mathematical programming with multiple objectives: A tutorial, *Computers Operations Res.*, 1980, **17**, 5–31.
4. DYER, J. S. — Interactive goal programming, *Mgmt Sci.*, 1972, **19**, 62–70.
5. ZIONTS, S. AND WALLENIUS, J. — An interactive programming method for solving the multiple criteria problem, *Mgmt Sci.*, 1976, **22**, 652–663.

6. IGNIZIO, J. P. Generalised goal programming—an overview, *Computers Operations Res.*, 1983, **10**, 277–289.

7. STEUER, R. E. *Multiple criteria optimisation: Theory, computation and application*, 1986, Wiley.

8. ZELENY, M. Linear multi-objective programming, *Lecture Notes in Economics and Mathematical Systems*, No. 95, 1974, Springer-Verlag

Thesis Abstract (Ph.D.)

Technologies in telecommunication sector: An assessment with particular reference to telephones, teleprinters and switching equipment in India by A. V. Sivarama Prasad.
Research supervisor: N. Somasekhara.
Department: Management Studies.

1. Introduction

A country's survival and growth depend on planning and utilisation of its resources efficiently. For any planning and decision-making system, technology information, forecasting and assessment are essential[1]. Rapid technological progress and increased rate of obsolescence of technologies necessitate technological forecasting and assessment for any planning process In this regard, telecommunication sector is typically a high-technology area of industrial activity where obsolescence rate is very high and it needs proper planning. While telecommunication is a cardinal sector for modern society and country's socio-economic development, in India it is in a primitive stage with obsolete technologies, low quality and reliability of products and services, repeated imports and unsatisfactory performance in general. Among the various factors responsible for this unsatisfactory state, those related to technology are considered to be crucial. Attempts to ameliorate the Indian telecommunication sector has necessarily to be associated with the choice of suitable technologies. Further, to be able to avoid imports and to compete with other developed countries more sophisticated technologies are required. The choice of technology decision, a strategic one having long-term implications requires the application of modern management techniques[2,3]. Also the choice of technology is a multiple criteria decision-making (MCDM) process. In view of the foregoing, technology forecasting and assessment have been performed with reference to telephones, teleprinters and switching equipment in the telecommunication sector.

2. Objectives and methodology

This study focuses on the three equipment and attempts to investigate into the problems of technology requirements, forecast and assessment. More specifically the objectives are: (i) to identify the existing and future technologies, (ii) to perform technology forecasting, and (iii) to select alternative and suitable technologies for India with the help of technology assessment. The methodology of the study is based on a combination of technology-forecasting and assessment methods. By using Delphi and analytical hierarchy process (AHP) methods, various best and suitable technologies among available ones (existing and future technologies) and their trend have been obtained for the three equipment in Indian telecommunications. To generate information, a Delphi survey was conducted in three rounds and in all there were 73 panelists involved in the study. Delphi is an intuitive consensus of expert

opinion from large group of people in a systematic way[4,5]. The analysis was made at four levels, namely, alternative technologies, alternative equipment, design technologies and manufacturing technologies for the three equipment. The probable occurrence of various technologies has been forecast and the impact coefficients of each one estimated. For selecting alternative and suitable technologies for the Indian environment, the AHP has been used. The relevant parameters were identified with the help of literature and supported by the panelists. The AHP is a multiple-objective multiple-criterion decision-making approach that employs a method of multiple paired comparison to rank order alternative solution to a problem formulated in hierarchical terms[6]. The Delphi results were used as inputs to the AHP for selection of alternative technologies. The combination of these techniques gives selected technologies and their trend for Indian telecommunication sector. The steps involved in choosing technologies from available technologies are shown in fig. 1. The likely period of occurrence and impact coefficients were obtained from technology forecasting exercise for 327 technologies relating to the three equipment. And the priority indicators were determined for the 1097 technologies from technology assessment exercise.

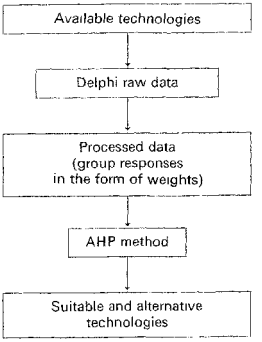

FIG. 1. Steps involved in choosing technologies.

3. Results and conclusion

The selected technologies were obtained from technology forecasting and assessment exercises. The final choice of technologies was determined on the basis of the period of occurrence, the impact coefficient, the priority indicator and a number of other techno-economic parameters. Technology planning and policy imperatives regarding the final choice of technology, their import and indigenous development and commitment of resources have been obtained from this study. It is observed that future technologies are better than the existing ones on most criteria with respect to the three chosen equipment. Therefore, India has to develop newer technologies indigenously or import immediately to catch up with the latest trend in telecommunications of developed countries. Some of the conclusions underline the importance of component manufacturing technologies. The results of the study provide some direction towards the optimal use of resources in the telecommunication sector. Further, the study also figures out inadequacies in the candidate technologies thereby providing some clues for their rectification, and some direction towards the optimal use of resources. The trend of demand, the profile of costs, the requirements of manpower and the need for investment relating to the alternative

technologies investigation will be useful to academicians, R & D managers, policy makers of government and any telecommunication organisation.

References

1. *United Nations' Technology policies and planning. India*, Asia and Pacific Centre for Technology Transfer, Bangalore, Prepared by N. Somasekhara, Indian Institute of Science, 1986, p. 221.
2. SHARIF, M N. *Management of transfer of technology and development*, 1983, APCTT, Bangalore.
3. PORTER, A. L. *et al* *A guidebook for technology assessment and impact analysis*, 1980, Elsevier.
4. MARTINO, J. P. *Technological forecasting for decision making*, 1983, Elsevier.
5. LINSTONE, H. A. AND TUROFF, M *Delphi methods – Techniques and application*, 1975, Addison-Wesley
6. SAATY, T. L. *The analytic hierarchy process*, 1980, McGraw-Hill.

Thesis Abstract (M.Sc.(Engng))

A solid modeller for parametrically representable shapes by Deepa Krishnan.
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Department: Computer Science and Automation.

1. Introduction

Computer-aided design (CAD) is of paramount importance in industry. Initially, CAD systems were two dimensional (2-D), but they could not provide computer assistance to mechanical engineering applications because these systems involve three-dimensional (3-D) objects and the spatial relations among them. To model such objects, CAD systems were extended to allow a volumetric approach, in which simple solids could be added and subtracted to form more complex shapes. Such systems are used for the design and manufacture of machine parts to produce tool paths for the numerically controlled (NC) machining of parts and to enable robots to generate the required arm motions and gripper actions. Existing systems for this purpose include PADL[1], TIPS[2], BUILD[3] and many others. The existing geometric systems have some drawbacks. They are: 1) shape operations involve a lot of computation and hence are slow in nature, 2) lack the ability to adequately handle parametric shapes, 3) use only the constructive solid geometry (CSG) or boundary representations (B-Rep)[4] while an integration of schemes is necessary to ensure application independency, 4) a conceptual model for representing shapes which also serves as a database model is lacking in these modellers. Such a model is essential in order to easily represent constraints on object orientations as well as to represent procedural information, and 5) the algorithms for boolean operations and volumetric property calculation are performed by software in these systems which is a slower approach for the interactive design of complex 3-D objects. An approach amenable to hardware implementation is necessary to improve the speed of response of these modellers and to enable them to be used in a real-time environment. To remedy some of these defects we have introduced GEODERM (GEO metric Design system using the Entity-Relationship Model) which embodies a new approach based on a conceptual object model, the parametric model[5]. Some of the salient features of GEODERM are illustrated in the next section.

2. GEODERM: The organization

The solid modeller has been implemented on an Intel Series III 16-bit microcomputer development system. The microcomputer interfaces with a graphics subsystem using an 82720 graphics display controller and CORE standard graphics software. The parametric model[5] used in this modeller represents shapes at a conceptual level. This model allows easy description of parametrized shapes encountered in machine part design, permits user-friendly object modelling and also representation of more semantic information related to a shape. Representations of CSG and B-rep solids are found to be very compact in GEODERM. The parametric model is represented in terms of E-R constructs[6] and since the E-R model is used only to describe the conceptual schema, the model is implemented as the relational model in GEODERM. The main software constituents of GEODERM are the Login module, solid definition language (SDL), solid manipulation language (SML), the menu-interface module and the output procedures module. The definition and manipulation languages enable interactive definition and manipulation of CSG and B-rep objects. Boundary solids can also be defined using sweep methods[4] in the menu-interface module. This module incorporates a number of procedures based on Euler operators[7]. These procedures interface with CORE standard graphics software and allow a graphical translation of the commands in the menu-interface module. The output procedures module is based on octree representations[8] and performs boolean operations as well as calculates geometric properties. In GEODERM, CSG and B-rep schemes are used for the storage of objects in the database, while sweep representation schemes are used as a means of input and the octree scheme is used to perform boolean operations and evaluate volumetric properties. Thus there is an effective integration of many representation schemes. A new algorithm has been developed to perform boolean operations on shapes represented by modified-octrees (M-octrees). These octrees allow nodes of the types EDGE and VERTEX in addition to the BLACK, WHITE and GRAY nodes in conventional octrees[8]. As the boolean operation is being performed, the algorithm mentioned above generates a visual feedback to the user. This is unlike existing algorithms which traverse the resultant tree once more to generate the display. This algorithm also generates a sequence of Euler operators for the resultant solid when both input shapes are boundary solids. The languages used for the implementation of this solid modeller are the programming language Pascal and the 8086-based pseudo-high-level language PL/M-86.

3. Conclusions and extensions

The solid modeller presented in this thesis has the following advantages over the existing solid modellers.

1. An integration of four representation schemes enables GEODERM to exploit the advantages of each of these schemes.
2. Boolean operations are executed in linear time using M-octrees and hence are faster.
3. Validity checking (a test to see if an arbitrary set of faces encloses a solid) in the case of boundary objects is simplified by the use of Euler operators.
4. The conceptual model used in GEODERM specially facilitates the handling of parametric solids. The model allows easy representation of geometric constraints and procedural information and increases the application independency of the model.
5. The use of octrees makes the entire system amenable to hardware implementation using parallel architectures. If implemented in hardware the speed of response of the modeller is greatly increased.

To facilitate the implementation in hardware the thesis also proposes a parallel architecture for the solid modeller consisting of a host processor, a geometric operations processor, two octree generation machines, a boolean operations processor as well as a processor to calculate volumetric properties.

The efficient hardware design of each of these modules would be a valuable extension to the work presented in the thesis.

The present version of GEODERM handles only polyhedral objects with or without holes and curved surface solids bound by cylindrical surfaces. More primitives such as cones, spheres and tori can be added to the system and a method by which the system can be extended to model sculptured surfaces is also discussed. Lastly, the thesis also suggests the use of the modeller in conjunction with an expert system for vision and computer-integrated manufacturing applications to enhance the capabilities of such a system to store and manage information about three-dimensional solid objects.

References

1. VOELCKER, H , *et al*	The PADL-1.0/2 system for defining and displaying solid objects, *ACM Computer Graphics*, 1978, **12**, 257–263.
2. OKINO, *et al*	*TIPS-1*, Institute of Precision Engineering, Hokkaido, University of Sapporo, Japan, 1978.
3. BRAID, I. C.	*Designing with volumes*, Ph.D. Dissertation, University of Cambridge, 1973.
4. REQUICHA, A. A. G	Representation for rigid solids: Theory, methods and systems, *ACM Computing Surv.*, 1980, **12**, 437–464.
5. KAWAGOE, K. AND MANAGAKI, M.	Parametric object model: A geometric data model for computer-aided engineering, *NEC Res. Dev.*, 1984, **72**, 23–32.
6. CHEN, P. P.	The entity-relationship model—Toward a unified view of data, *ACM Trans. Database Systems*, 1976, **1**, 9–36.
7. MANTYLA, M	A note on the modeling space of Euler operators, *Computer Graphics Image Processing*, 1984, **26**, 45–60.
8. MEAGHER, D.	Geometric modeling using octree encoding, *Computer Graphics Image Processing*, 1982, **19**, 129–147.

Thesis Abstract (M.Sc.(Engng))

Passive localization of sound source in shallow waters–simulation studies by K. Anil Kumar.
Research supervisors: P. S. Naidu and T. S. Vedavathy.
Department: Electrical Communication Engineering.

1. Introduction

Localization of sound source in shallow-water channels is an important topic of research. Two recently proposed algorithms for source localization, namely, TDOA estimation by phase reconstruction[1] and a HR technique, multi-image subspace algorithm (MISA) proposed by Mohan[2] were studied. The limitations of TDOA estimation technique and finite data effects on MISA are reported.

2. Theory

2.1. *TDOA estimation technique*

By estimating the time delays of direct and the primary reflected rays the source in a shallow water can

be localized using three-point method. The time delays are related to the cross-spectrum. Assuming the spectrum of signal source to be broad-band, the auto-terms and the cross-terms in cross-correlation function can be separated. Using an iterative technique[1], the time delays of different rays can be estimated from the phase of the cross-spectrum.

2.2. *Multi-image subspace algorithm*

MISA based on eigen structure decomposition, exploits the information about shallow-channel geometry and has already been shown to possess all the advantages of eigen structure methods, under asymptotic conditions[2,3].

Using an M-element vertical line array, the covariance matrix R of the received signal is formed, *i.e.*,

$$R = A W W^{+} A^{+} \sigma_s^2 + \sigma^2 I$$

where A is the steering matrix ($M \times N$), W the signal vector ($N \times 1$) corresponding to source and its ($N-1$) images, and σ_s^2 and σ^2 the signal and noise powers, respectively.

Since source and its ($N-1$) images are coherent WW^{+} is a ($N \times N$) matrix of rank 1. It can be shown that $\cap = W^{+} A^{+} A W \sigma_s^2$ is the eigen value of $AWW + A +$ and the corresponding eigen vactor is AW.

Let $E = [e_2 e_3 \ldots e_{N-1}]$ be the noise subspace of the covariance matrix R. Since eigen vectors corresponding to different eigen values in a covariance matrix are orthogonal, we have $|E^{+} A W|^2 = 0$.

Since only noisy estimates of E are available, the above orthogonality relation may not hold good. Therefore true source position is given by $p(r, Z) = [|E^{+} A W|^2]^{-1}$.

3. Results and conclusions

3.1. *TDOA algorithm*

The cross-correlation function forms the basis of TDOA estimation technique. It is found that when the source and the receiver are close to the surface or bottom boundaries the autoterms and the cross-terms in the correlation function are interleaved, *i.e.*, some of the cross-term delays are smaller than the autoterm delays. Therefore true delay estimation is not possible. Also as the range increases, the auto- and cross-terms are clustered and it is difficult to separate them easily using a window. Thus TDOA estimation technique fails to localize the source which is close to the channel boundaries or which is far off from the receiver.

3.2. *MISA algorithm*

The finite data effects on MISA were studied in detail. The effect of snapshots and array SNR (ASNR) on detection probability was studied. The detection probability increases with increasing snapshots and/or ASNR (fig. 1). By defining a finer resolution window around the true source position the bias or shift in peak position was studied. It is found that for low ASNR or low snapshots bias exists. MISA is independent of source-receiver positions, provided ASNR and/or snapshots cross certain lower bounds. For example, at 10 dB ASNR, while 100 snapshots are sufficient to detect the source, at 0 dB ASNR as high as 1500 snapshots are required.

The behaviour of MISA estimates as a function of data length has been compared with the performance measure[4]. It is shown that for a given ASNR, beyond a certain minimum number of snapshots, the performance of MISA is independent of source/array location. For a smaller number of snapshots the estimates follow the performance measure (fig. 2).

Finally, the sensitivity of MISA to channel undulations is also studied. The undulations, modeled as

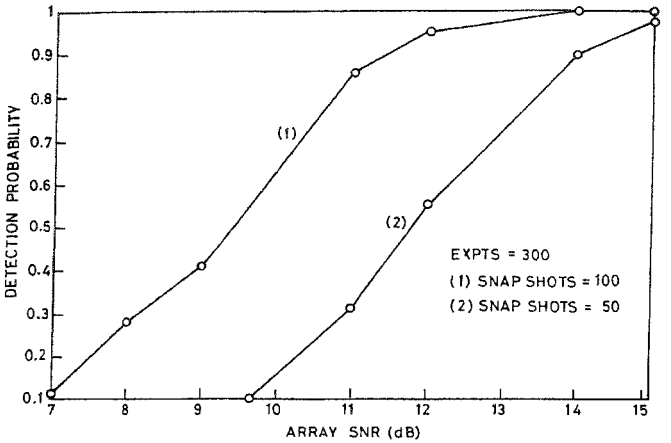

FIG. 1. Detection probability – Array SNR curve. $Z_S = Z_R = 50\lambda$; $R = 1000\lambda$.

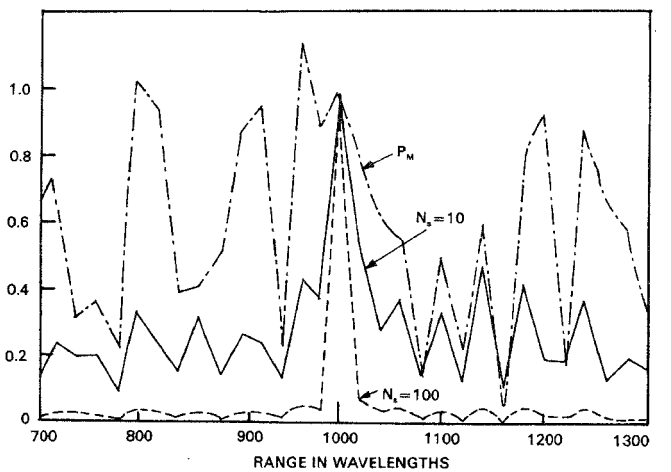

FIG. 2. Performance measure and average parametric spectrum as a function of range, $R = 1000$ $Z_S = Z_R =$

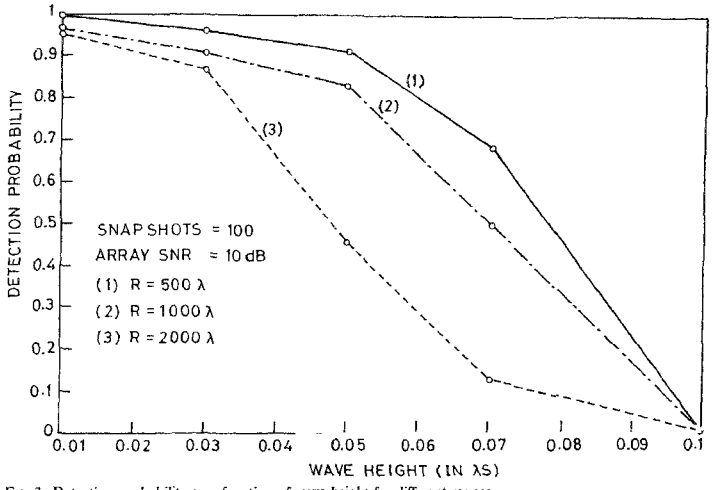

FIG. 3. Detection probability as a function of wave height for different ranges.

sinusoidal fluctuations severely affect the MISA estimates, particularly as the range increases (fig. 3). The detection probability decreases drastically for the undulations of the order of 1/10th of wavelength. This reemphasizes the need for accurate knowledge of the channel parameters and geometry in order to effectively employ MISA.

References

1. HOU-CHAO-HUAN — A new method for passive locating of unknown source by using a vertical dipole receiver, *ICASSP*, pp. 15.8.1–4, 1984.

2. KRISHNAMOHAN, P. G. — *Source localization by signal subspace approach and ambient noise modeling in shallow waters*, Ph.D. Dissertation, 1988, Indian Institute of Science, Bangalore, India.

3. NAIDU, P. S., *et al* — On source localization in shallow water channels, *Indo-US Workshop on Systems and Signal Processing*, Bangalore, Jan 8–11, 1988.

4. DANIEL SPEILMAN, *et al* — Performance analysis of the *MUSIC* algorithm, *ICASSP*, pp. 35.24.1–4, 1986.