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A SIMULATED REAL-TIME ENVIRONMENT FOR VERIFICATION OF ADVANCED WATER NETWORK CONTROL ALGORITHMS

Computer assisted control of water distribution systems represents a large scale real-time data processing problem and demands an integrated approach to software design and testing. The availability of relatively inexpensive computer hardware and the increasing importance of energy and resource savings has led to the increased interest in sophisticated control schemes. Objectives of these schemes include the minimisation of production cost, improvement of the security of supply and the ability to ensure the correct operation of water works and pumping stations. Testing and validation of the analysis and control software may be achieved with the aid of a real-time simulation system. In this way the performance of a management software can be evaluated against a realistic model of the network under a range of operating conditions. A secondary benefit of an integrated simulation, monitoring and control software design is the ability to provide a useful operator training aid, which includes system dynamics, measurement uncertainty and control facilities.

The present paper describes both the individual modules within the package and the subsystems coordination. The simulation methods are described with emphasis on real-time operation. The major monitoring tasks: observability determination, state estimation and bad data detection, are explained and are shown to exploit the particular structure of the problem. Numerically stable, sparsity exploiting techniques have been used in the design of the estimator, and the combinatorial methods avoiding any floating point computations underlie the observability test.

An account of modern software engineering techniques used in the design of the package is given and the issue of software portability is being addressed.

1. INTRODUCTION

During the past fifteen years there has been a considerable investment of research in the field of water distribution systems. The reasons for this research are complex but perhaps the most important is the fact that a typical water network has expanded to the point where the ability of the human operator to perceive and

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process information became a hindering factor in achieving optimal operational decisions. The availability of relatively inexpensive computer hardware and the increasing necessity of improving a cost/performance ratio has led to a radical change in the philosophy of water system operation, which manifests itself in the emergence of computerised telemetry which can potentially give greater insight into the system state. However, this potential can only be fully realised if the appropriate information processing software is employed. Because of the high dimensionality of water distribution systems the task of computerised monitoring and control represents a large scale real-time data processing problem and demands an integrated approach to software design and testing. Objectives of this task include the minimisation of production cost, improvement of the security of supply and a coherent picture of the system presented in terms of variables which are convenient for use both by a human operator and control algorithms. Testing and validation of the monitoring and control software may be achieved with the aid of a real-time simulation system. In this way the performance of higher level software can be evaluated against a realistic model of the network under a range of operating conditions. A secondary benefit of integrated simulation, monitoring and control software is the ability to provide a useful operator training aid, which includes water system dynamics, measurement uncertainty and control facilities.

The present paper describes the major components of the water system simulation, monitoring and control facility which has been developed during the past five years. This system provides a test-bed for water system control research, and allows the evaluation of various control policies against a realistic model of water distribution network under a wide range of dynamic operating conditions. It has also been used in the industrial environment for processing the actual telemeasurements.

In Section 2 the simulation methods are described with emphasis on real-time operation. Sections 3 and 4 discuss the monitoring and control tasks and Section 5 the co-ordination of the individual subsystems. Experience gained with the system is given in Section 6 and some conclusions are drawn in Section 7.

2. SIMULATION

A water system simulation facility is a necessary component of an integrated software system for monitoring and control of water distribution networks. The simulation subsystem allows higher level software to be tested and evaluated without recourse to 'live' telemetry data. It also provides a valuable tool for control policy studies, software diagnosis and operator training. Figure 1 shows the major data base elements required for simulation. The exact data blocks contain information of the physical state of the network such as pipe connectivity, parameters of hydraulic elements, load conditions and valve controls. The data includes a network topology representation in which nodes and pipes correspond to either individual or

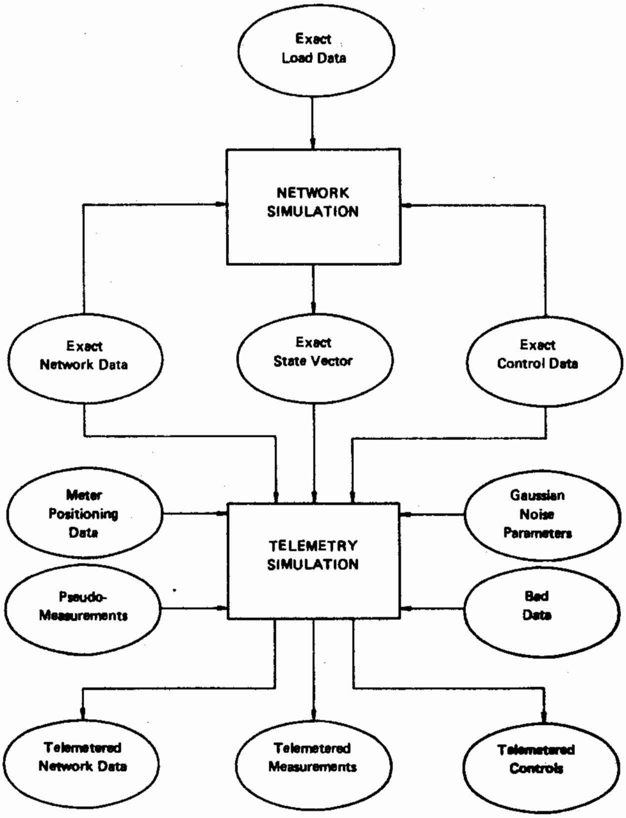

Fig. 1. Simulation subsystem

aggregated hydraulic elements. The parameters of these elements have numerical values determined using an off-line parameter validation utility.

The simulator applies a nonlinear algebraic model of the network in conjunction with a set of low order differential equations representing reservoir and control valve dynamics to produce telemetry information. It has been found that the direct summation of valve openings and the trapezoidal integration of reservoir volume combined with sparse Newton Raphson solution technique give satisfactory results. In its present form the simulator enables the operator to change the setting of any control valve in the network, to alter the node connectivity pattern, and to introduce additional nodes representing leakages in the network. The simulation programs also enable the level of measurement noise to be varied and the gross measurement errors to be introduced into the telemetered data base.

The mathematical model of the water system which has been used was selected so as to avoid excessive computational burden. However, in order to permit a realistic response to load variation it was considered most important to retain individual models for each pumping station. Dynamic load models have not been incorporated within the present simulator in order to simplify computations. Constant water consumptions are therefore imposed, which are determined from a predefined load curve.

The simulator, monitoring and control algorithms can be executed on Perkin Elmer or DEC range of minicomputers using an OS32 or VMS real-time multi-tasking operating systems. The highest priority in the software suite is assigned to the simulation task. In general, the simulation imposes the major computational load on the system, but with the slow system dynamics an approximate real-time operation is possible with over 200 nodes.

3. MONITORING

The purpose of the monitoring tasks is to create a reliable data base in which the raw observations have been systematically processed in order to filter out the effects of measurement and transmission noise and also to eliminate the presence of gross errors caused by equipment malfunction. This data filtering is possible only if the full use is made of the information about the network structure and measurement accuracy.

The monitoring subsystem consists of three major tasks: observability determination, state estimation and bad data detection/identification, which are described in the following sections. The corresponding data base structure is given in Fig. 2.

3.1. OBSERVABILITY DETERMINATION

In on-line operation, the availability of a routine to check whether the water system is observable or not significantly affects the efficiency of the estimation process. Before the execution of the state estimator the observability task determines whether the currently available measurements provide sufficient information to allow the computation of the state estimates. If this is the case, the estimation proceeds. Otherwise, the system is unobservable, and the estimator will not be able to calculate the states for the whole network. This situation may arise as a result of meter or telemetry failure, changes in network topology by means of valve controls, and also as a consequence of the elimination of measurements previously identified as bad data. In this case, the observability routine identifies observable subsystems so that, in a subsequent step, either the state estimation is applied to the subnetworks of the original system, or appropriate pseudo-measurements are added. Combinational topologically-based observability algorithms have been developed [1]–[3] and proved to be very efficient in on-line environment. These algorithms can also provide a valuable assistance in off-line meter placement studies.

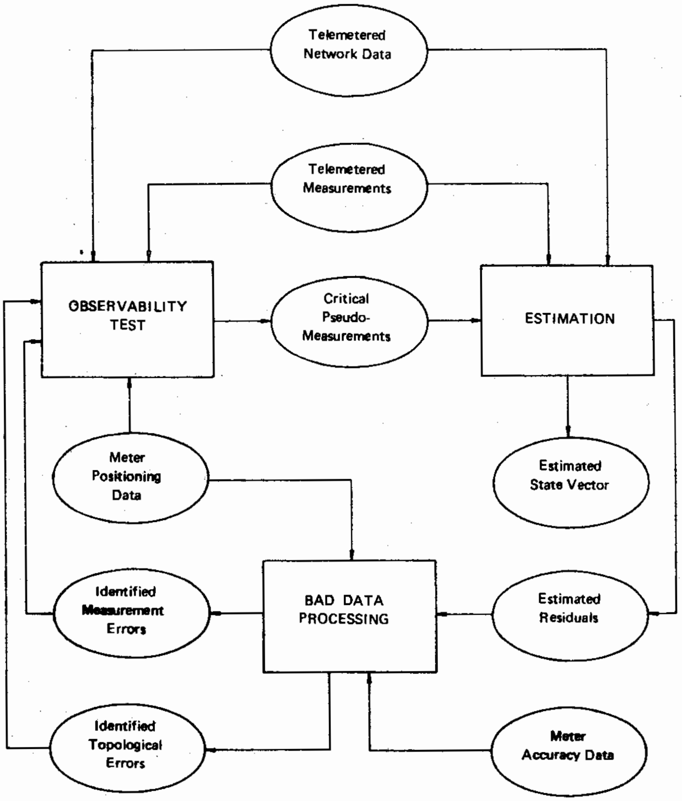

Fig. 2. Monitoring subsystem

The first method formulates the observability problem using a measurement-to-edge bipartite graph in which a maximum matching is sought. The edges which have a measurement assignment are subsequently used to build an observable spanning tree. If such a tree cannot be found directly, a loop-breaking procedure, also based on the matching method, may be applied to reassign measurements and link forest components. This method is particularly efficient for the systems with measurement redundancy.

The second method is based on the direct search for an observable spanning tree in the augmented network graph. During construction of the tree its edges are labelled so as to enable efficient reassignments in case the method identifies only an observable forest and at the same time some measurements remain unassigned. The method makes use of the depth-first-search procedure of TARJAN [10], modified to cater for constraints defined by the dynamically changing measurement set.

3.2. STATE ESTIMATION

A characteristic feature of water distribution systems is that the measurements available are limited to a few readings of heads, consumer loads and pipe flows which, in themselves, do not provide a complete picture of the system state. Cost considerations frequently severely limit the number of measurements, with the result that many network flows and heads remain unknown. This otherwise inadequate information can, however, be combined with a knowledge of the topology of the water system and predictions of consumer loads to provide a complete specification of flows in all pipes and heads in all network nodes. Techniques which implement such a combination are known as state estimators. If sufficient basic measurements are available, the state estimation can also act as a filter for incoming data by providing a comprehensive check. The measurement redundancy is used to identify erroneous measurements and to eliminate them from further processing.

Numerically stable algorithms based on the least squares and least absolute values optimisation techniques have been developed and implemented [4], [9].

The least-squares estimator is based on the formulation proposed by SIEGEL [11], where the initial measurement equations and the least-squares optimality conditions are incorporated into a supermatrix system which is then solved using an appropriate factorisation technique. The method is numerically stable since the formation of the normal equation, which augments the condition number is avoided altogether. Also, the numerical efficiency of the method is superior compared with Golub's and Peters–Wilkinson's methods, particularly in the case of low redundancy levels.

The second state estimator, incorporated in the package, employs a least-absolute values optimisation criterion. By doing so, the estimator is able to reject bad measurement data during the estimation process so that the final state is defined only by the valid measurements. Details of an efficient implementation of this algorithm exploiting sparsity considerations are given in [4].

3.3. BAD DATA DETECTION/IDENTIFICATION

The necessity of systematic approach to bad data detection/identification became apparent only when the telemetry systems had been installed in the water industry. The problems with consistency of telemetered data stimulated the development of procedures capable of detecting whether erroneous measurements are present in the measurement set, and if this is the case, to identify the faulty observations so that they can be either eliminated or replaced by pseudo-measurements.

In practice, the bad data are caused by a variety of reasons, such as failures of communication links, defective meters of transducers, inaccurate models of pseudo-measurements, etc. All these errors fall into two categories: gross measurement errors where the numerical value of a reading is incorrect, and topological errors where the topological representation of the network is not compatible with the actual system state.

If there is a high enough local measurement redundancy, it is sometimes possible to reject erroneous data by prefiltering the measurements. This procedure consists of simple limit checks and plausibility tests based on comparisons of redundant measurements. However, this is usually not effective if bad data are either corrupted by less than a certain percentage of the meter reading or the neighbouring measurements are not directly comparable with the faulty one – flow and pressure being an example. In practice, in order to be reliable the bad data detection and identification procedure must use the results of the state estimation process.

The output from the estimator provides essentially two pieces of information: one is the value of the state estimates and the other is the magnitude of the discrepancies between measured and calculated values of variables of interest. Methods which make use of this information and which take into account meter positioning and measurement accuracy (see Fig. 2) have been developed [9] and proved to be effective in distinguishing gross measurement errors, leakages and incorrect valves status in the network.

4. CONTROL

The validated measurement information produced by the monitoring subsystem forms the basis for the design and implementation of an efficient water network control. The operation of water networks is optimised in two respects: minimisation of pumping costs by scheduling as many as possible pumps during the off-peak hours, and minimisation of water losses via distributed leakages by regulation of system pressures.

Although the overall problem of optimisation of pumping cost can be expressed mathematically, the solution for medium and large scale systems is beyond the scope of currently available computing techniques due to the unpredictive nature of the scheduling problem, inherent water system dynamics and complicated nature of operational constraints. Presently available analytical methods based on decomposition techniques [5] or dynamic programming [6] are only computationally feasible for small systems. Application to real-life water networks implies the use of heuristic methods [7].

The valve control function is introduced in order to minimise the overpressures in the network, particularly during the night period when the pressure rises due to decrease of consumer demand. As the complexity of a distribution network grows, this task becomes more and more difficult, and the average overpressure tends to increase. This in turn results in an increased energy cost, increased volume of distributed leakages and higher risk of major bursts. In complex networks the volume of leakages can amount to approximately 25–30% of the total production and consequently represents the main potential for improvement of water system economy.

An efficient algorithm which takes into account current consumer loads and supplies to the system has been developed using linear programming technique [8]. This makes it possible to take full advantage of the sparse structure of the problem and to achieve solution times compatible with real-time control requirements.

The monitoring and control software described in this paper takes the static pump schedule, devised off-line, for the whole 24 hour period and calculates dynamically the optimal settings of selected control valves. The controls are presented to the operator who can subsequently implement them having the complete validated information about the system state (Fig. 3). The operator is aided by the graphical display program which allows for continuous zooming onto any part of the network and, according to the chosen magnification coefficient, for a varying amount of detail about the network to be displayed.

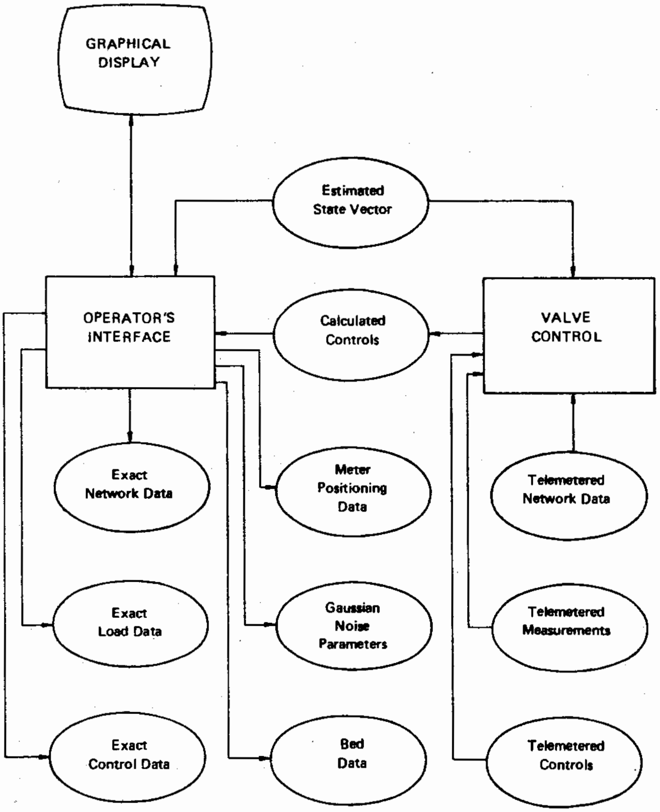

Fig. 3. Control subsystem

5. SUBSYSTEM COORDINATION

The software which has been described in previous sections is coordinated to form an integrated system in the manner illustrated in Fig. 4. The configuration of the overall scheme highlights similarity with conventional automatic control systems. Information is retrieved via the telemetry task and is validated by the monitoring subsystem which consists of observability determination, state estimation and bad data processing tasks. These tasks are on-line to the actual system, since the data is passed between them without a human intermediary. Feedback control is affected via the optimal valve controls which are implemented by a human operator, thus being off-line. Such a structure is natural at the initial stage of computer-assisted water system control, and it can be easily converted into a full on-line scheme since the controls are updated after every telemetry scan.

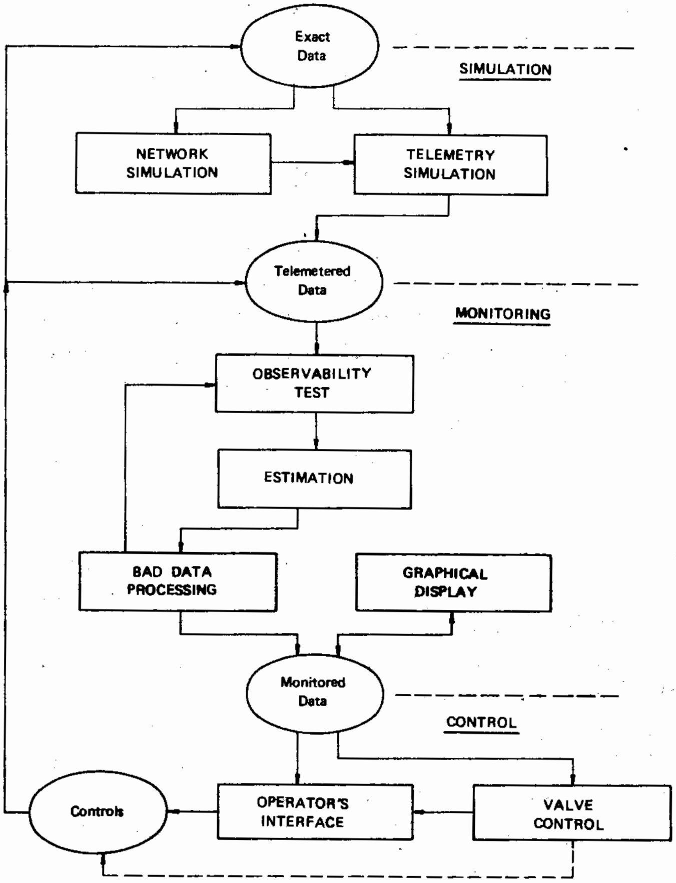

Fig. 4. Subsystem coordination

In order to achieve a degree of robustness, a highly modular structure of the software has been adopted. Each task communicates with others through shared memory areas with specified access priviliges. The timing of task execution and synchronization has been achieved by reference to semaphores and event keys in shared data. Every task or subsystem is capable of being initiated or aborted at any time without compromising the integrity of the overall system (although various data may become outdated). In particular it would be quite straightforward to replace the telemetered data generated by the simulation subsystem with the one supplied by a telemetry computer. The software is written in FORTRAN 77 and process communication and synchronisation have been implemented using the facilities of the OS32 and VMS multi-tasking operating system [13].

6. EXPERIENCE

The water system monitoring and control software has been implemented on two modern 32-bit minicomputers Perkin Elmer and DEC–VAX. This hardware has proven to be very satisfactory with respect to memory capacity and input–output bandwidth. However, the software is highly demanding on processor time and a trade-off between algorithm sophistication and run time becomes necessary for large networks. Future improvements in processing speed would enable explicit handling of probabilistic aspects of water distribution systems which are at present approximated by deterministic equivalents.

Research on water system software in an integrated framework has increased the emphasis placed on algorithm robustness, bad data rejection and man–machine interfaces. Application of FORTRAN 77 language with appropriate real-time extensions has been found to be satisfactory, although the future availability of ADA may offer many advantages. Inter-task communication has been achieved by means of shareable memory segments, appearing as common blocks within the FORTRAN programs, and consequently providing a rapid access capability. Coordination of tasks in the suite has been obtained using the computer manufacturers standard operating system, without recourse to a central controlling task or monitor. This approach enabled the use of the powerful hardware than otherwise would be required.

7. CONCLUSIONS

The development of an integrated simulation, monitoring and control suite has been found to be essential in order to conduct research into operational control aspects of water distribution systems, since it enables the consideration of realistic environments. Data rates and noise corruption are readily included and processor loading is immediately available from the simulated control system. The introduction of sophisticated control software also implies the need for operator training facilities in which the man–machine interface, control functions and the dynamics of the network are fully represented. Inevitably the integration of an advanced control capability and operator training facilities will become increasingly important in future. A research program is under consideration to combine artificial intelligence techniques and expert systems with the man–machine interface requirements specific to water control systems.

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