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Real-time model based diagnosis of gas turbines

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ABSTRACT

With the increasing complexity of problems and applications being tackled by automatic monitoring and diagnosis systems, it is becoming essential to tackle different aspects of the problem with different paradigms. Some applications are complex now, but the most optimum tool for each aspect of the problem must be well integrated with other optimum solutions for other aspects of the problem, in order to achieve more robust and complex systems. For an interesting class of problems a single monitoring and diagnosis paradigm is no longer adequate.

This paper describes the work of integrating various reasoning paradigms being conducted in the ESPRIT project, TIGER, for gas turbine monitoring and diagnosis. In this work we combine real-time rulebased diagnosis techniques with real-time situation assessment techniques and qualitative simulation model based diagnosis. These techniques are integrated using a task architecture. The work is being applied to an industrial gas turbine at Exxon Chemical in Scotland, and an Auxiliary Power Unit turbine at Dassault Aviation in France.

INTRODUCTION

A gas turbine is an essential part of the modern process and power generation system. Powerful gas turbines are often the primary driver of a power station or for major process plants. Because of their high cost they are normally not deployed in a redundant manner, and hence their availability is critical.

In addition, with the increasing complexity of these systems and the gradual spread of their use, the gap between a typical engineer's understanding of the working of the turbine and its real performance is increasing (See Figure 1). A final important aspect is that maintenance costs of such critical items of equipment are very high.

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Many companies would like to move from a calendar or running hour based maintenance strategy to a condition based system. In order to achieve this, powerful monitoring and diagnosis is needed to identify whether the turbine is working properly or problems are developing [9].

The TIGER project (ESPRIT III Project: 6862) is developing a real-time situation assessment system for gas turbines. This combines real-time artificial intelligence based diagnosis techniques using more traditional rulebased approaches with qualitative models and simulation of the turbine behaviour.

The role of each of these are described in turn (See Figure 2).

REAL-TIME DIAGNOSIS

The fastest cycle of diagnosis is implemented by the KHEOPS rulebased. This system transforms a first order rulebased system into an optimised network [5]. Not only does this network execute at a very high speed (10,000 rules per second), but also provides a guaranteed response time. This is a crucial element in calculating the real-time characteristics of the system. For the TIGER project diagnostics this provides very high speed execution and fault detection, as well as diagnostics relating to the alarms generated by the turbine are encoded in this system.

For several years, TIGER partners have had experience with an approach that solves appropriately the guaranteed response-time problem. This approach has been implemented into a system, called KHEOPS, which has been tested on several industrial applications, with good performance (e.g. an upper bound of one tenth of a second for a rulebase of 5,000 rules on a 68K processor, see [8,13]).

The Knowledge Representation compatible with an upper bounded response-time should necessarily be decidable. Hence, KHEOPS relies on some extension of propositional logic (i.e. variables quantified over finite domains, multi-valued attributes considered at various time-points). Although KHEOPS does not take into account time (as a history of the working memory), it performs a monatonic reasoning that matches some output to the current state and history of the working memory.

Since a system working in a closed loop with its environment has a well defined input (it does not require the flexibility of an interactive system), one can specify, along with a KB, what will be the input attributes and the output attributes. Hence it is possible to get through all "interesting" states that the system can meet, and to perform at compiling time the usual search and rule chaining for each such state. This compiling stage ends up with a deterministic decision network, whose internal codes are input attributes and whose leaves are output attributes. The longest path in such a network is the upper bound in the response time.

This pre-processing is performed by the KHEOPS compiler, together with a consistency checking of the KB. Compiling is very costly (a NP-hard problem), and may require the decomposition of the KB.

The second powerful tool is a situation assessment system IxTeT [6] and [7]. The IxTeT system includes a time manager to control the temporal history of parameters. The information to the monitor is encoded as time oriented situations and predictions. When an event occurs on the gas turbine, the relevant predictions are made as to future events. These predictions include normal operation of the system as well as possible specific faults scenarios.

The IxTeT system is based on a time-map manager, relying on the time point algebra as well as the restricted interval algebra. It is the only known system that has linear performances for both updating and retrieval data (while maintaining the consistency of the constraints).

IxTeT time-map manager has been developed for planning, as well as for situation assessment which is relevant to TIGER.

In the situation assessment system a schema is a collection of events (or situations), together with their temporal constraints. Temporal primitives are points or intervals, and constraints are either symbolic (time-point or restricted interval algebra relations) or numeric. Instance of events are supposed to be time-stamped to enable the verification of temporal constraints. The system takes as input occurrences of events, labelled and stamped. It is able to recognise instances of described situations and to trigger corresponding tasks (at various points of a situations development). It can hypothesize situations when partially recognised.

The IxTeT system monitors the time evolution of parameters to ensure they are consistent with the predictions. As part of the monitoring strategy, the definition of normal operation is encoded as situations. Any deviation from this is indicated by the system as a first level indication of a problem. In addition, specific fault situations are identified, these are only relevant if they are triggered as compared to the normal predictions which are only relevant if they are not triggered. Although the IxTeT situations can be encoded by hand, the project is exploring a means of creating these predictions automatically from the qualitative simulation of the turbine.

QUALITATIVE SIMULATION

A qualitative model [15] of the gas turbine is being developed in the CAEN formalism. This captures the knowledge of the components of the system and how they react to dynamic changes. For example, if the load increases then the speed of the output shaft will decrease. This will cause the control system to increase the amount of fuel which increases the amount of power through the combustion process and increases the shaft speed. This type of causal sequence is encoded together with the constraints and dependencies between variables. The qualitative simulation is

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then used to make predictions of responses to specific events. These are then encoded as IxTeT situations or used by the model based diagnosis strategy.

Numerical analysis will be used to provide identification of dependencies and constraints for the qualitative system. This is particularly important for a system performing incremental tracking of the dynamic system over time. Numerical techniques are used to identify the dependencies between parameters and to clarify their influences. This is then used to generate some of the constraints needed by the qualitative simulation.

Model Based Diagnosis

CA-EN (Causal Engine) is a prediction and supervision tool which was devised and implemented at LAAS-CNRS by the DHP-AQSE Group [1,2,3,4]. CA-EN is aimed at reasoning on line, to support tasks required in dynamic systems supervision such as: (1) assessing the value of non-observable variables and the current state of the system; (2) making predictions; (3) determining corrective actions in case of faulty behaviour; (4) explaining the process behaviour by referring to its history.

This tasks are performed using a model-based approach with explicit causality and time representations. In this approach, the prediction module has a central part for it performs the tracking of the system's dynamic behaviour. For diagnosis purposes such as in TIGER, this module is foreseen to be used (1) to provide the reference dynamic behaviour to which observed behaviour will be compared, thus allowing discrepancy detection; (3) to perform candidate generation by searching backwards in the causal dependency graph of the models (2) to test fault candidates and proceed to their discrimination.

CA-EN Knowledge Representation Formalism

Representation of Time in CA-EN

For several reasons, we have chosen to use sampled time. As in conventional sample-and-hold systems, the system state is assumed to be constant between two sampling instants. This is performed by using a logical clock accordingly set to the swiftness of the process. Among other things, a linear temporal scale allows us to easily evaluate state durations and event dates and to be synchronous with the observations coming from the process which are plotted into the model [14,15]. In order to deal with temporal features (delays, durations), we use a temporal manager based on a time-point algebra.

Qualitative Automata

The process variables are either numeric (real-valued) or symbolic-valued. We refer to the quality space for a numeric variable as a partition of its value set; the quality space of a symbolic variable equals its value set. Quality spaces are assumed finite

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and linearly ordered. A (qualitative) state for a variable is any element of its quality space. A (qualitative) variation for a numeric variable is any amount of change within the chosen temporal unit. We call the variation space for a numeric variable the set of all possible variations within the unit of time. Similarly to the quality space, a variation space is a finite partition of a real interval. Symbolic variables have no variation space.

For every variable x_j, we consider an elementary dynamic system. It consists in 3 qualitative functions :

* a transition function A, that represents the dynamics, or evolution of the variable x_j in the absence of external effects.
* an input function B for representing the contribution of external effects, i.e. the variable variation x_j due to other variables variations Δx_i, $\{x_i; i \neq j\}$.
  a combination operator ©

Then the basic equations of the elementary q-automata are :

$$\Delta x_j = B(x1, x2, \ , x_n; i \neq j)$$

$$x_j(t+1) = A[x_j(t)] \; © \; \Delta x_j$$

Relationships

We use a two-level representation scheme for the description of the relationships between the process variables: a local constraint level and a global constraint level.

The local constraint level is in agreement with our perception of a physical process as a net of interacting q-automata influencing one another. This is represented by a oriented graph in which the paths reflect the perturbation flow causality. The influences supported by the edges of the graph allow one to represent the causal-dependency-type knowledge. There are two kinds of causal relations : (1) influence-based relations which are concerned with cause-effect interactions among numeric q-automata only; (2) information-based relations which are concerned with information about q-automata states. Whereas the latter relations establish a mapping between the causing and caused variables quality spaces, the former establish a mapping between their variation spaces [2].

An influence-based relation is described by means of a predicate whose arguments specify the influencing q-automaton, the influenced q-automaton, activation preconditions of the causal relation, the weight of the influence, its delay and its response time. Actually, the weight of the influence is automatically calculated from the description of the relative order of magnitude of the influences of causing q-automata with respect to other q-automata. This is performed using the relative order of magnitude formalism. An information-based relation is simply described by a

The global constraint level is composed of functional numeric constraints relating possibly more than two process variables associated with interval domains, e.g. constraints arising from physical laws. In other words, a general constraint is any numeric equation (in the classical sense) in which each unknown is supposed to take on interval values.

Prediction Algorithm: Causal Qualitative Simulation

Simulation gives us a way to implement the classical prediction/correction procedure as the basis of the reasoning leading to monitoring the behaviour of the system and detecting early deviations from the nominal behaviour [14,15]. Our algorithm includes three steps : (1) perturbation propagation (2) state updating; (3) consistency filtering.

Perturbation Propagation

This is mainly concerned by the problem of influence combination which occurs at the lower level. In other words, having two or more influencing q-automata and knowing their respective deviations (w.r.t. a qualitative variation space), how to combine their influences (with different sensitivity degrees represented by a fuzzy relative order of magnitude) to provide the resulting deviation on the influenced q-automaton. The particular case of two influencing q-automata can easily be handled with correspondence tables [3]. The solution that we devised for the general case of causal dependence upon several influences is a generalisation of the correspondence tables to n-dimensional spaces. It is implemented as a generalised weighted sum (whose weights are calculated from the sensitivity degrees) of marginal influences [4].

State Updating

For every q-automaton, this step performs the combination of the current variation Δx resulting from the above computation with the q-automaton's most recent state to update the q-automaton's state, i.e. it performs the operation $x(t+1)=A[x(t)] \copyright \Delta x$.

Consistency Filtering

Perturbation propagation and state updating are performed with qualitative calculus and it might be that the result provides several possible qualitative values for the updated states of the q-automata. The upper global constraint level is then used as a consistency filter (mainly for numeric-type q-automata and by using interval algebra calculus) which allows the system to discard some of the values. The final result is then matched to the quantity space of the corresponding variable and the likeliest state is as the one minimising a generalised distance [1].

Transactions on Information and Communications Technologies vol 1, © 1993 WIT Press, www.witpress.com, ISSN 1743-3517

DIAGNOSIS BASED ON PROGRAMMABLE LOGIC CONTROLLER PROGRAMME

A key element of any large industrial system is that part of it is controlled by programmable logic controllers. These provide for sequencing and logical dependencies. For the gas turbine domain they provide the indications of alarms and the conditions leading to an alarm. They also provide information with regard to the causes of alarms, trips or failed start-ups. As part of the TIGER project we are developing a mechanism to develop diagnostics based on the programmable logic controller code. The emphasis is on developing techniques that can automatically translate a computer description of the PLC programme into a diagnosis system. Currently we have implemented a topology analyser for the PLC code and the work on developing the diagnostics portion is underway.

DIAGNOSIS ARCHITECTURE

These various tools are integrated through the key steps of the monitoring and diagnosis task. (See Figure 3).

The overall diagnosis architecture is similar to commonly used model based diagnosis strategies [12]. The key idea is to divide the diagnosis process into a series of tasks. This type of division of the problem into task is not unique. However, what is different is the way model based techniques are combined with the non-model based techniques. This provides a conceptual framework for dividing the problem and integrating the various tools. Much of this integration is performed at system set-up and compiled time. For example, at runtime the IxTeT situations are already fully defined and prepared for execution depending on the incoming data patterns. Similarly, the KHEOPS diagnostic rulebased will be fully compiled and ready for activation when necessary.

From the software integration viewpoint, these tools run in parallel as integrated processes working on the appropriate data inputs and providing output to the system manager. The control of these modules in not the focus of this paper.

The first task is parameter prediction, either using static limits, the predictions of numerical analysis or states from the qualitative model, a prediction is made of the expected values of the parameters. By viewing this as a task, the different techniques naturally integrate to provide a single parameter prediction step.

The parameter predictions can be divided into three sets. Predictions based on static thresholds or based upon pre-compiled expressions and using the value of a parameter and an individual time point rather than the evolution are performed by the KHEOPS system. Pre-computered or pre-compiled situations and time evolutions of parameter values are monitored by the IxTeT tool.

Transactions on Information and Communications Technologies vol 1, © 1993 WIT Press, www.witpress.com, ISSN 1743-3517

Finally, the CAEN qualitative simulator is used to make predictions at runtime of evolutions of variables, although there is some overlap between these predictions and the hand coded situations in IxTeT. The primary focus of the CAEN predictions is to assist with unknown or new fault conditions. The other primary role for the KHEOPS tool is the diagnosis of problems relating to alarms or trips to the turbine. In this situation, the required knowledge is based on the ladder logic description. This portion of the diagnostic rulebase is normally idle, however, when either an alarm occurs or a trip occurs this portion of the rulebase is executed to identify the precise cause from the multiple possible causes.

The second task is fault detection. In this step the real-time data acquired from the gas turbine is compared with the parameter predictions. Any violations are then characterised. The fault detection step compares not only current values but also parameter histories. The fault detection step is performed by KHEOPS, IxTeT and CAEN on their respective types of input data.

The third task is candidate generation. In this step the system generates hypotheses of what possible deviations from the expected model of the system would result in the observed behaviour. The TIGER project is addressing this through a series of fault models. The qualitative models can be extended to include models of the components reflecting failed states. Currently being explored are methods of compiling the normal and fault models into a set of situations reflecting the expected predictions of each scenario. Based on this the candidate generation step is a matter of matching the deviations to the appropriate fault model.

The above technique works very well for situations which have been anticipated in advance, either by hand or with fault models. However, there is a class of problems that are not practical to anticipate in advance, this may be because of the large combinatoric explosion of using fault models or the rarity of a situation that does not justify the induction by hand. For this purpose the qualitative simulation and causal dependencies are used with a model based diagnosis strategy to help to identify the cause of a problem. This overall strategy is related to consistency based diagnosis.

In general the split between the IxTeT and CAEN tool is that IxTeT monitors for pre-compiled situations where as CAEN is focused on situations not covered by the pre-compilation. In general, this would include new problems or problems not anticipated in advance. Note, that in some cases IxTeT situations will have explicit recognition of the fault or the results of a fault model.

A final task is candidate discrimination and verification. In this step the proposed candidates are used to make predictions of new parameter values and ensure they are consistent with the observed behaviour. Because the qualitative models can be compiled into the IxTeT situations, this step in some cases has been pre-computed. It is also possible to mix hand generated situations with automatically generated situations.

The complete diagnosis system is being designed to work in a UNIX environment connected on-line to the data acquisition of the gas turbine. The current data acquisition system provides approximately 80 analogue and 80 digital parameters at one second intervals. This time interval is adequate for a large number of faults, although there is a class of faults which happen much more quickly and will not be detectable with this current data acquisition system.

Within the gas turbine domain the majority of the problems will exist for a long period of time, although they must be detected based on the one second time interval data. For this reason, it is critical that the diagnosis system is able to base its analysis on high resolution data, but the speed of diagnosis of some fault categories, particularly unknown fault situations, does not need to proceed this quickly. There is also a class of fault conditions which only occur under special operating conditions. These can be considered intermittent faults. In order to properly capture and detect these, it is vital that the diagnosis system is able to run at the same speed as the data acquisition. The execution speeds of KHEOPS and IxTeT provide this.

CURRENT STATUS

At the current time the TIGER project has a rulebased diagnosis system running daily connected to a gas turbine at Exxon Chemical [10,11]. It is providing diagnosis at once per second intervals. This system has been in use for over one year and has been instrumental in identifying a major plant fault. This has resulted in significant payback to the end user. In addition, the system has provided a large set of test data on which to base further test and development, and given us considerable experience in the problems the gas turbine experiences during a normal year. The development of qualitative models and their integration with numerical techniques and the situation assessment tools is being conducted at this time. Considerable real data has been acquired from the existing system illustrating various faults. These are being used to guide and test the development.

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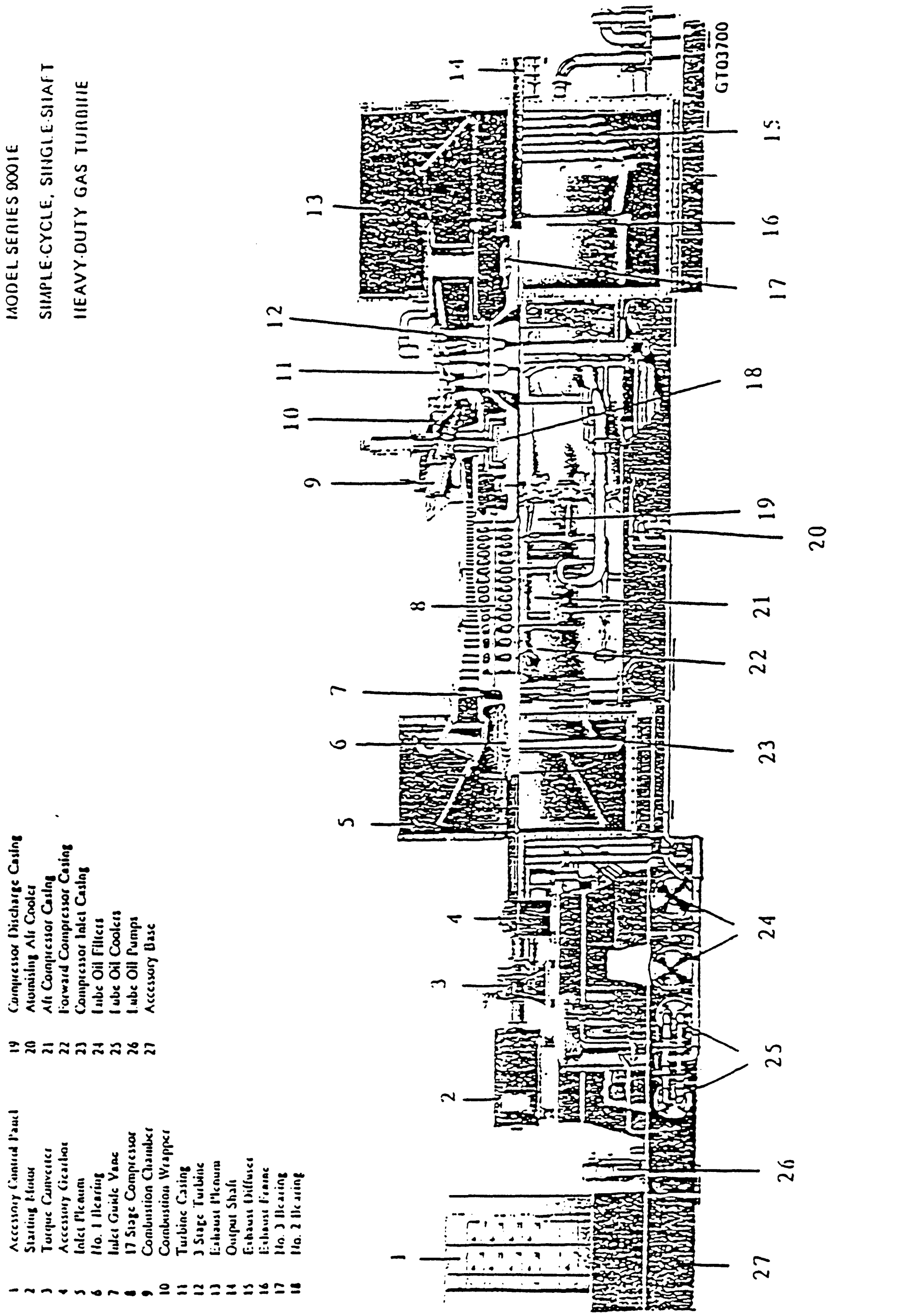

Figure 1. Example of Typical Gas Turbine

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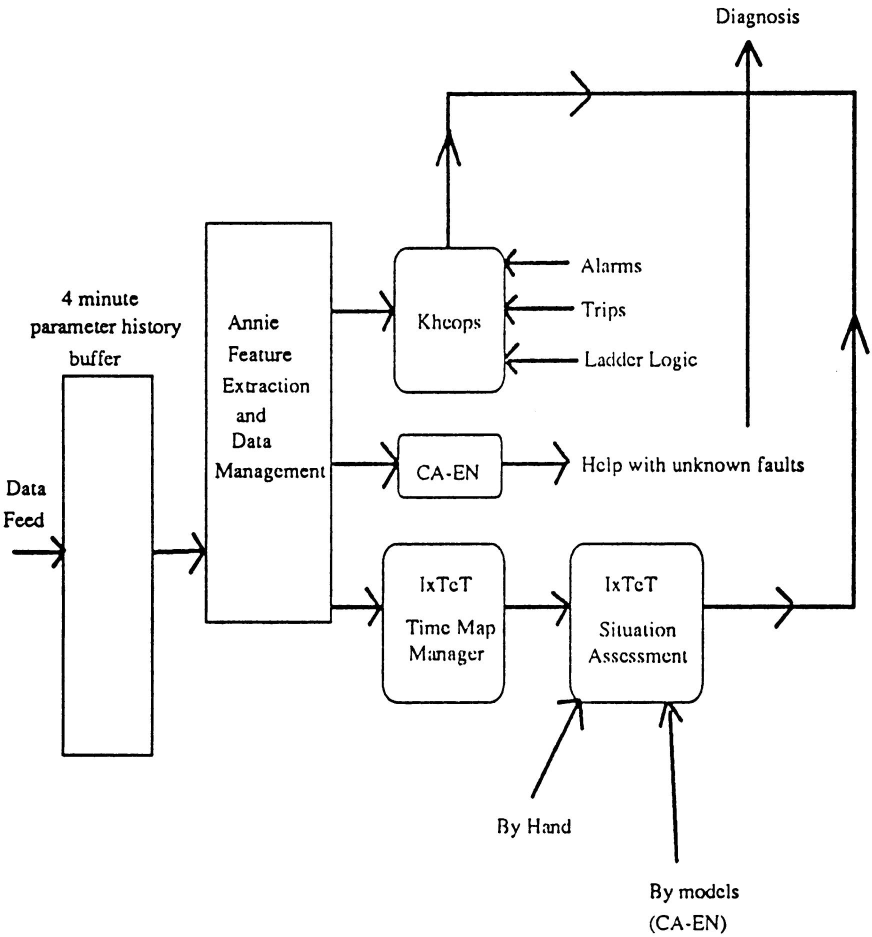

Figure 2. Integration of Tools

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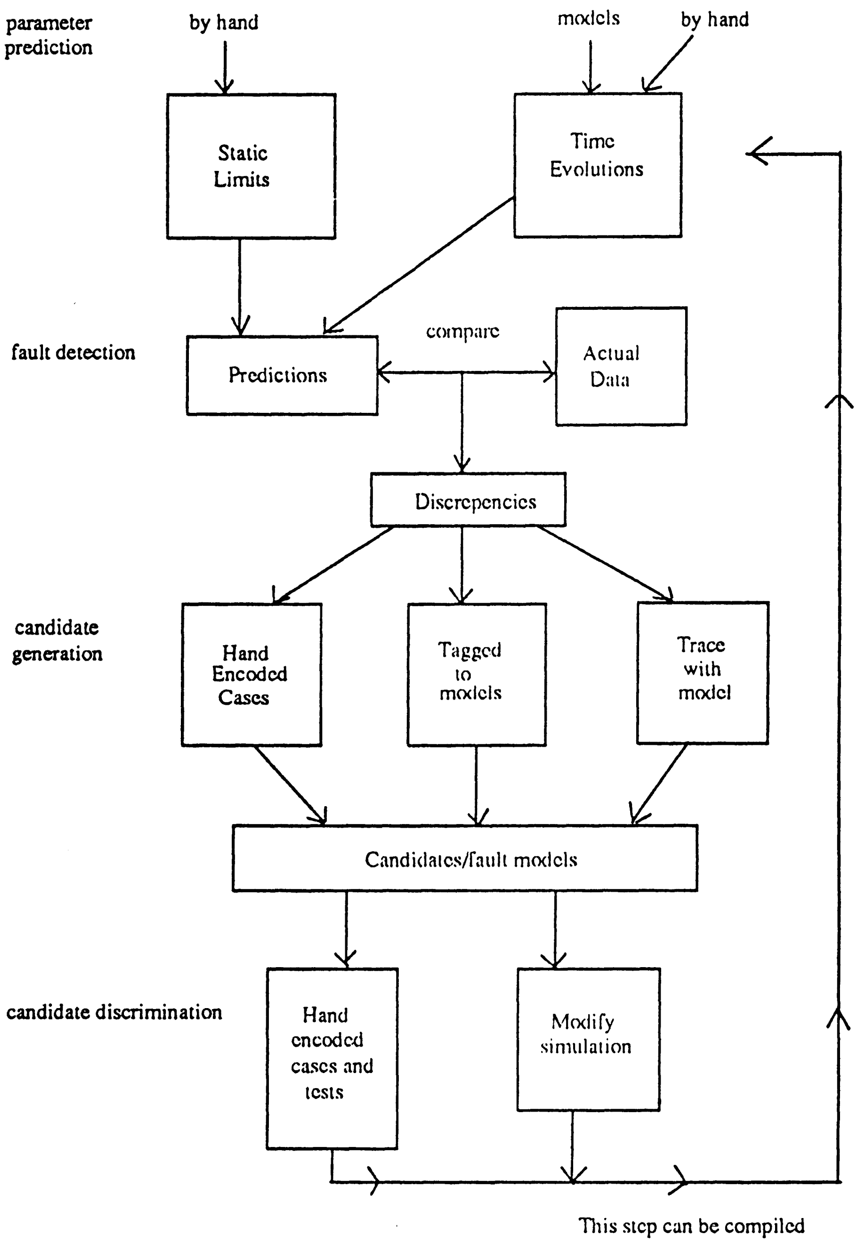

Figure 3. Diagnosis Strategy