CENTRAL ADVICE SYSTEM FOR FLEET MANAGEMENT AND OPERATIONS
Improving the safety and reliability of rolling stock

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1 INTRODUCTION

Due to the changed role in current society, the requirements for mass transit products have changed dramatically over the last few years. The impact of social-economical changes lead to the necessity for polyvalent service and technical staff. Technological evolution has made systems more complex, "intelligent" and interactive. On-board systems are therefore required to support higher comfort, increased availability, better maintainability, reduced life-cycle cost and increased efficiency.

Safety, availability, reliability, maintainability and life cycle costs of transport systems are directly determined by the efficiency in fault diagnosis throughout the life cycle. Improved efficiency in operational diagnosis comprises;

- Significant increase in the level of diagnosis automation.
- Significant increase in the coverage of problems.
- Significant increase in the accuracy of diagnosis by tuning symptoms, additional tests and actions.
- Ensuring guaranteed response times for critical on-line diagnosis situations.

To cope with the mentioned evolution, a Central Advice System (CAS) for rolling stock (trains, trams, underground, light-rail transport systems, etc.) is under development as a decision support system for drivers, maintenance personnel and fleet managers. This development takes place within the framework of the European research and development project BRIDGE (ESPRIT Project 22154). BRIDGE specifically aims at real-time diagnosis of very large technical applications. The overall goal is to significantly improve diagnosis efficiency in operations and reduce the efforts required in supporting actions.

In this paper, the theoretical background of the BRIDGE tools will be discussed, the functionality of the Central Advice System will be presented, followed by the application of BRIDGE in CAS.

2 THE BRIDGE-PROJECT

The BRIDGE project aims specifically at real-time diagnosis for large technical applications. Two main problems are encountered due to the size and complexity of such applications. First of all, the definition of the domain knowledge requires attention. The relations between faults, failures, symptoms and repair actions can be fairly complex and sometimes unknown. The efforts for are related acquisition, representation and maintenance of this domain knowledge should be minimised. Secondly, the be able to work in real-time within the framework of embedded on-board systems, the search process for the diagnostic reasoning should be predictable and have a guaranteed response time.

The BRIDGE tools comprise two separate tools; the Support Function Tool (SFT) and the Operational Diagnosis Tool (ODT). The SFT is an off-line tool to support the acquisition and maintenance of the knowledge base. The knowledge representation is based on case-based reasoning (CBR); a reasoning technique that allows for a definition in the form of each fault independently in terms of symptoms, etc. CBR then allows searching through these so-called cases to find the cause and to suggest corrective actions. Development support within the SFT includes the evaluations of integrity, coverage, accuracy and the real-time behaviour. After definition and analysis of the knowledge, and to generate from the definition a dedicated real-time diagnosis system, the ODT (see ref. 5). The ODT performs the on-line diagnosis of the alarms, and presents the diagnosis and additional tests that can be performed or questions to narrow down the search process. The ODT does not directly access the knowledge base of the SFT. A problem is diagnosed in the real-time kernel of the ODT, which is based on a novel approach in real-time expert systems (see ref. 3).

2.1 Representation of Domain Knowledge

Facts and their relations represent domain knowledge. The facts of diagnosis applications comprise the physical configuration of the technical application that is diagnosed, possible health states, operational modes, operator levels, and the alarms, symptoms, tests, interventions and faults. The total number of facts in large technical applications, as emphasised in the BRIDGE project, can be in the order of tens of thousands.

Problems, or failures, are represented as relations between these facts. Different types of models can be developed from such relations; i.e. probabilistic models, causal models or fault-trees. Due to the complexity and number of on-board systems, it is almost impossible for human experts to explicitly define and maintain all facts and their relations consistently. Acquisition of a consistent application model would be too costly. In practice, it becomes impossible to develop such a model (see ref. 6).

Diagnostic knowledge of the kind encountered in transport systems is implicitly available in the description of failure cases. A case describes a specific failure only by the occurring facts. The relations between these facts are not defined explicitly. A new problem is diagnosed by remembering similar fault cases. The action of the most similar case is reused as a diagnosis for the new problem. Additional tests can also be retrieved from these similar cases. The relevance of additional tests can be identified from case similarities and their information gain. This technique has already been successfully applied in a modified form in the BRIDGE prototype (see ref. 5).

Because case-based diagnosis avoids the explicit compilation and definition of relations, the efforts required for development and maintenance of diagnosis systems can be much smaller than for other techniques. Possible disadvantages of case-based diagnosis are a reduced accuracy and increased response time. Several BRIDGE features solve these disadvantages:

- In the knowledge representation, the general application knowledge is separated from the failure behaviour. General application knowledge is represented in the Configuration and Systems Description (CSD). Failure behaviour is represented as cases in the fault-base. The CSD only contains well-defined application knowledge that is independent of the behaviour of the application. Even for large industrial applications this knowledge is well defined and can be acquired relatively easy. An example is presented for CAS (see further).

- A diagnosis task defines the operational conditions for diagnosis, such as the technical subsystem of a new problem, alarm level, operator level, and the maximum available effort and time for executing tests and actions. These conditions thus bound the diagnostic reasoning.

- A failure case represents only one occurrence of a set of inputs, its causing fault and its intervention. In practice, however, a fault may cause other symptoms or results as well, and an intervention may be appropriate for several failures and faults. Several failure cases could be abstracted into a single case for a fault or intervention. This abstract or fault-case, is defined by the complete set of inputs and interventions. Each of these inputs can be associated with a certainty factor.

- The accuracy of diagnosis can be improved when general background knowledge about the application is included in case-based reasoning. Furthermore, the CSD enable essential evaluations of the knowledge base.

- Searching a fault-base directly would seriously degrade the response time for on-line diagnosis. Instead, use is made of a novel approach to real-time expert system techniques, representing the domain knowledge, and is used during on-line diagnosis in the ODT.

2.2 The Search Network

To address the problems of searching large amounts of cases, a fault network was developed (see ref. 5 and 6), resembling the Rete network (see ref. 1). The network relates diagnoses inputs to faults and interventions. The initial developments used the network on-line as search medium, and initial evaluation has shown to give a satisfactory behaviour (see ref. 6) and confirms several major advantages over other diagnostic approaches:

- The size of the network is minimised and contains no redundant nodes or relations. Computer memory can be reduced for large applications.
- Search is highly efficient for interactive systems. The network is only searched forward in a predictable manner.
- All possible faults and actions are searched in one pass through the network, allowing for the simultaneous treatment of multiple symptoms.
- The diagnostic strategy for a particular diagnosis task determines the categorisation of inputs. The strategy is thus inhibited in the network structure.
- Any input is immediately propagated through the output layer and avoids any backtracking or look-ahead search.
- The search procedure and size of the network strongly reduce the response time for diagnosis.

2.3 Analysing Coverage and Accuracy

The network of the BRIDGE prototype has been redeveloped and extended with sub-networks for the CSD and the SFT evaluations. The network facilitates the evaluation of integrity. Any integrity conflicts are detected as ambiguous links during generation of the network. The intermediate nodes, as categories of common inputs, facilitate the evaluation of, coverage and accuracy. The coverage of the knowledge base is the set of faults that can be diagnosed and the set of interventions that can be identified in the ODT. An indication of the coverage can be provided from the set of resolved and unresolved operational problems. Such a problem can be simulated in the network. Matching intermediate nodes identifies the coverage of faults and interventions for such a problem. The accuracy of a diagnosis depends on the accuracy with which a fault or intervention can be identified and depends on the additional information that can be obtained in operational conditions. The accuracy of the ODT should therefore be evaluated for different diagnosis tasks and operational conditions. The results of such an evaluation reveal the need for refinement or addition of tests and questions.

2.4 Real-Time Expert System Techniques

Still, the network does not allow for real-time response time during search. For on-line use, an alternative approach is employed based on novel real-time expert system techniques. A state-based architecture is adopted, where only one process is active at any time, having exclusive access to any global data and no process will be pre-empted. In addition, a case-set compiler is used to address the problems of guaranteeing hard real-time response times (see ref. 3), generating deterministic C-functions for the search paths.

The response time of the ODT depends on the amount of knowledge to be searched and the search process itself. The response time thus depends on the diagnosis task and operational condition. The BRIDGE project specifically emphasises the hard real-time requirements of operational diagnosis. The real-time characteristics of the envisaged system have to be assessed in the SFT. The response time of the on-line diagnostic system must match the requirements specified for the transport system. There is a need for formal analysis of the resulting on-line expert system that will be derived from the network structure, potentially in combination with the systems in which it will be embedded. A highly novel methodology for specification, analysis and synthesis of real-time systems is the Q-methodology (see ref. 4), developed from an original approach by Quirk which allows specification and verification of all required timing characteristics during the design of real-time systems. This methodology was further developed and combined with the Object Modelling Technique (see ref. 7) within the framework of the LIMITS project, supported by the European Union.

3 EFFICIENCY IN OPERATIONAL DIAGNOSIS

The rapidly evolving developments in rolling stock equipment strongly increase the complexity of problems occurring during service. Managing these problems during service and maintenance becomes very difficult. For each problem that appears, several possible causes exist, often linked with multiple systems and with a high impact on further service. The solutions to be taken depend on the impact on safety and service, and on the available resources. The decision process involves expertise from different persons, such as drivers, engineers and fleet managers. Efficiency for managing problems depends on the efficient processing of information about the current status of the application, a vast amount of domain knowledge, and experiences from other experts.

A Central Advice System (CAS) (see fig. 1) can be employed to support this complex decision making process. Two distinctively different tools are part of the CAS approach (as in BRIDGE):

- Support Function Tool (SFT), to support the *off-line* development of the on-line diagnostic system. Coverage and accuracy of the on-line diagnostic system are verified and improved with new operational experience. Verification of the real-time characteristics takes place here as well.
- Operational Diagnosis Tool (ODT), which provides a real-time *on-line* diagnostic system to support drivers, maintenance teams and fleet managers.

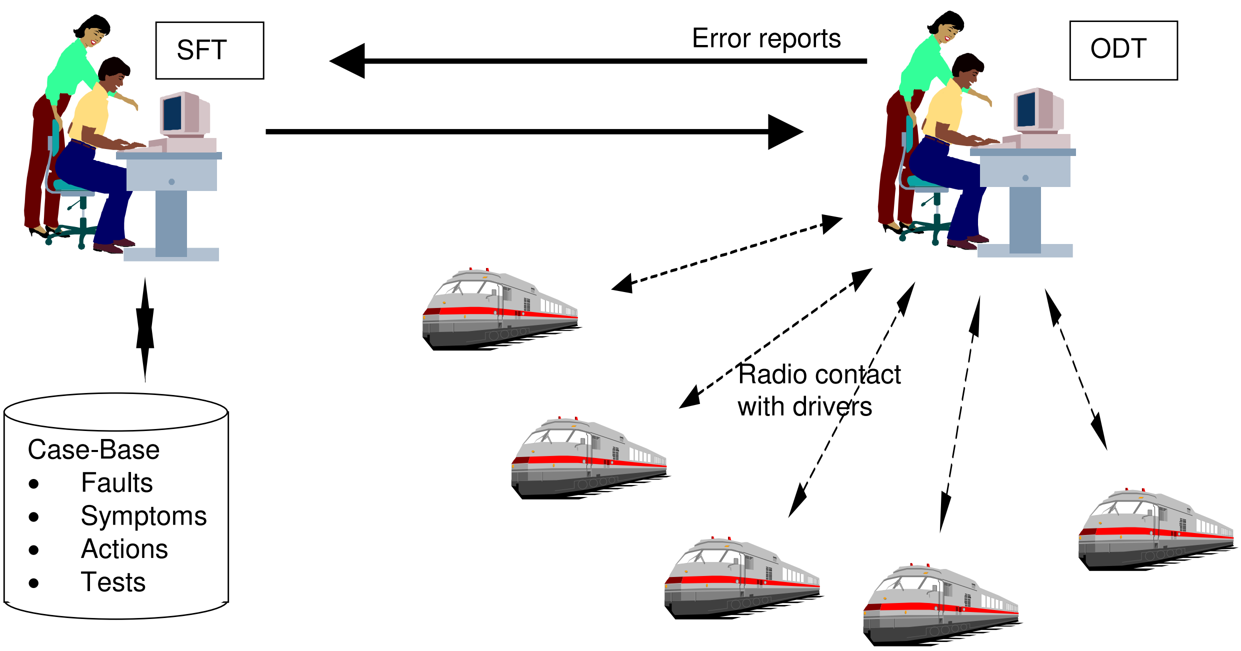

Fig. 1 A schematic overview of the Central Advise System

As is shown in figure 1, several types of users work with the two subsystems. The engineering departments work with the SFT on the definition and maintenance of the domain knowledge and generate the ODT. The ODT is used by the operators, which can be fleet managers that supervise the dispatching of trains, or for example maintenance teams that use the tool for in-depth searches.

3.1 Support Function Tool

The Support Function Tool assists in the development and maintenance of the Operational Diagnosis Tool. This comprises the definition of the knowledge, verification of the consistency and the coverage, verification of the real-time characteristics, analysis feedback reports from crew, etc.

3.1.1 Knowledge definition

The knowledge of system engineer(s) and system developer(s) is defined in two parts:

<u>Configuration and System description</u>	The configuration of a fleet is defined as a hierarchy of trains, vehicles, systems, components and spare parts. Furthermore, lists of possible health states, operational modes, operator levels, tools, etc. can be defined for each application.
<u>Fault-Base</u>	This is the case-base (see ref. 5) with all anticipated faults and failures of the fleet and its on-board systems. The complexity of inter- and intra-system behaviour of large industrial applications poses a tremendous problem for the development of diagnostic tools (see later).

The procedure for defining the knowledge is as follows. Engineers start by defining the configuration and system description, describing in an object-oriented manner the physical and logical composition of the trains. Then, the fault base has to be defined, describing the faults, symptoms, tests and test results in relation to the configuration and system description.

3.1.2 Network generation, analysis and knowledge compilation

The SFT automatically generates the search network upon request, for example after an update of the knowledge base. Because the experience of all users is recorded and updated in the knowledge base, it is automatically shared among all others users after a next update. After this, the earlier mentioned analysis and verifications take place:

- The integrity of the knowledge base is automatically maintained in the SFT. Any integrity conflicts are prompted back to the user for modification.
- The coverage of the knowledge base is estimated from the resolved and unresolved cases in the history. Newly encountered cases can be added to the knowledge base.
- The accuracy of diagnoses can be evaluated for different diagnosis tasks. Accuracy can be improved by (re) defining tests and questions.
- Real-time requirements of the ODT for a diagnosis task can be estimated from the generated network.

Finally, the knowledge compiler compiles the network into C-functions that will operate in a state-based environment so to ensure guaranteed response times for the operational diagnosis tool.

3.1.3 Knowledge updating and extension

Initially, the fault base only contains anticipated faults and failures, i.e. those faults and failures that the engineers have thought of during the development of the system. During operation, however, additional faults and failures may become apparent, and also these failures and their interventions can be incorporated in the fault base. The engineers are presented with recorded failure descriptions and use the SFT to semi-automatically update the fault base. The information is automatically retrieved from the recordings and possible updates of the knowledge base are prompted to the user. Those updates can consist of modification of existing knowledge or of addition of new items. The user has the option to accept, modify, or reject suggestions. In this way, the fault base grows incrementally and reflects the corporate knowledge on diagnosis of trains within a company.

3.2 Operational Diagnosis Tool

The Operational Diagnosis Tool of CAS provides accurate and valuable information in real-time about any problem in a fleet, including their impact on the health state of the vehicle. It also suggests recovery actions to resolve or reduce the problem. The provided information and suggested actions are task specific:

- Drivers only receive information about interventions that can be executed within operational restrictions and within a certain time limit.
- Maintenance teams receive more detailed information about repairs, tools, spare parts, required efforts, etc.
- Managers receive information about train health states, impact on service, required efforts for interventions and spare parts requirements.

The inputs from all tasks are recorded in a history logging for later use and analysis (see 3.1.3).

3.2.1 Advice during service

During operation, events can happen which are critical for service or degrade operation. Such events trigger alarms to notify the driver. In most situations quick intervention is needed to be able to continue the journey or to keep the vehicle in service until the next maintenance activity.

The ODT of CAS supports a driver to interpret the available on-board information in an efficient way. An alarm is used as the starting point for the decision path. The ODT returns a prioritised list of possible interventions to the driver. Upon request, the ODT also presents details on the interventions and their consequences on service and safety.

When the input information in insufficient to accurately diagnose the alarm, the ODT requests additional information. A list of relevant additional tests and questions is presented for which the driver could return answers. The ODT only requests additional information that is relevant for the current problem and that can be obtained in the current operational situation.

3.2.2 Advice for maintenance

Diagnostic information from the on-board systems is used as primary input for more detailed diagnosis during maintenance. As with the service advice, the ODT proposes the most appropriate tests and questions that can improve the accuracy of diagnosis.

The diagnosis tasks for maintenance and service are somewhat different. Interventions for maintenance are for example to replace a “Line Replaceable Unit”. The tests and questions that can be answered are also different.

3.2.3 Advice for management

On short term, the information retrieved from the ODT can be used for planning of the actual corrective maintenance as well as for the preventive maintenance. Furthermore, the fleet manager and maintenance manager can accurately allocate the trains or vehicles for service or maintenance respectively.

On long term, the information retrieved from the ODT can be used to forecast and optimise resources, such as stock, parts, staff, workshop, and etc.

4 THE BOMBARDIER TRANSPORTATION-DIVISION BN TRIAL APPLICATION

CAS will be applied as a trial application on the new tramways of one of BN's customers. These tramways contain advanced electronic technology:

- Microprocessor-based systems (brakes, converter, doors, passenger information system, …) which have their own control strategy and auto-diagnosis.
- An integrated network system with communication channels based on the TCN standard of the TC9/WG22 committee (train network : WTB, vehicle network : MVB).
- An integrated alarm and diagnostic concept (see ref. 1), including a driver touch screen for alarms, a vehicle computer for non-volatile storage of diagnostic symptoms information, and the possibility to launch start-up, shut-down and maintenance test sequences.

4.1 Alarm and Diagnostic Symptom Information

Symptoms are generated for alarms and diagnostic symptoms. Symptoms are presented with following information:

- Location is specified by the unique vehicle number, car-body type (A or B), and system name.
- Unique symptom code and an associated plain text description. The code identifies a problem as accurately as possible.
- A first advice and a severity-level as an indication of the impact on service. The five severity-levels are health states:

Critical alarm	The driver has to intervene immediately. Most of these alarms can cause a service interruption, for example "service brakes on" during traction increase.
Disturbed service alarm	Problem degrades normal performance of the train, for example "Door out of service".
Warning	This serves only as general information to the driver.
Maintenance corrective	Problem has no direct impact on the service, but it is advised to resolve it after service. State is only available at the driver's screen at the end of the commercial service.
Maintenance preventive	Problem has no direct impact on the service and only has to be repaired during the two-monthly preventive maintenance period. State is only available by downloading the logged database.

4.2 Objectives

The main objectives of the trial application are to prove by experiment that the BRIDGE tool can:

- Improve train availability and safety. The severity level can be decreased occasionally for different problems from 'critical alarm' to 'disturbed service' or even 'warning' by advising the correct driver intervention during service.
- Decrease maintenance cost. Time and efforts can decrease by advising the correct repair action during maintenance.

The systems related to train safety and train availability are monitored. For the trial application these include the traction, converter, electrical doors, brakes (including electro-dynamic, mechanical and pneumatic), compressor and automatic train protection.

Models are available for the doors, pneumatic brakes and compressor system. Initially, the knowledge base for is created from models. The knowledge base is updated with experience feedback from the experiments. Experience feedback is thus the only knowledge source for the other critical systems.

The trial period will be performed in two main parts:
- February '98 until June '98. The BRIDGE alpha release will be used during vehicle testing at Bombardier Transport-Division BN-site.
- From September '98 onwards, the BRIDGE beta release will be used at the customer's site.

4.3 Practical Application Information

CAS will run under ™WindowsNT. For service, CAS will be installed on a desktop platform in the control centre room and will be operated by the fleet manager. Information is passed to the driver by phone. For maintenance, CAS will be installed on a portable PC and used in the field.

The development of the application and of BRIDGE is done using OMT/UML (Object Modelling Technique / Unified Modelling Language) methodology and the software is written in ™Microsoft Visual C++. The graphical user interface is ™Windows look and feel.

The knowledge base is implemented in ™Microsoft Access. The link to the BRIDGE tool is implemented using ODBC in such a way that other relational databases can easily be used.

5 CONCLUSIONS

A Central Advice System is has unique real-time/on line retrieval and off line update capabilities. The treatment of fault conditions encountered on modern trains is expected to improve significantly with the installation of CAS. Following advantages are emphasised:

- All knowledge is available for all personnel. Modifications of vehicle systems, complex or sporadic problems are distributed without difficulty.
- Information on problems treated in a temporary way during service is available for maintenance people.
- CAS provides a systematic approach to solving problems, which will decrease the efforts and number of spare parts wasted or damaged. The trial and error method, as often used, is only successful a first time in about 60 % of the problems.
- Direct (hypertext-) links present the electronic Maintenance and Repair Manual information for tests, questions, interventions and spare parts.
- Reporting on problems is simple, uniform, complete, and generated automatically. The fleet/train manager can make a short- and long term planning for people and spare parts for the maintenance of the vehicles.
- Knowledge of a fleet's health state allows for better allocation of priorities for maintenance and for vehicles for service.
- Training of personnel can be improved. Real-life situations can be simulated from the history of recorded problems. Training system and vehicle knowledge can be reduced, in favour of learning how to retrieve the information via CAS.

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