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AN EXPERT INTEGRATED APPROACH TO DESIGN AIRCRAFT ELECTRICAL SYSTEMS

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Abstract

In this paper we describe ALEX (Automatic Loom EXpert), a knowledge-based system which models the design process of aircraft electrical systems. In particular we are concerned with the design phase in which engineers define the electrical bundles and install them on the aircraft mock-up.

The aim of the paper is to describe how the introduction of knowledge representation and AI techniques can support engineers in designing the electrical system and significantly affect the electrical design process.

The basic role of ALEX is to support engineers in the phases of the design process that lead to the production of the wire diagrams and of the installation drawings.

ALEX solves different design problems with different AI methods and it is a good example of the complexity of design viewed as a knowledge-based problem solving activity. It applies rules, constraint satisfaction methods and search algorithms in combination with complex domain heuristics. Moreover, it is connected to a CAD system and complements it by making available in the CAD environment a design solution which takes into account system requirements, installation and electrical constraints, and not only geometrical data.

1. Introduction

In this paper we describe a system which models the design process of aircraft electrical systems. In particular we are concerned with the design phase in which engineers define the electrical bundles and install them on the aircraft mock-up.

The development of this expert system has been undertaken in Alenia at a point where the general concept of design is undergoing a striking cultural change. Design is now conceived as a more integrated process where concurrent efforts of different departments contribute from the beginning to achieve a common result and where the former clear-cut distinction between design and manufacturing is rapidly fading. This is partly due to new technologies and partly to the realization that the predominant cost drivers in the design process are the downstream changes and the resulting rework. When a product part has to be redesigned to take into account demands that had previously been neglected, costs increase and the product quality decreases. Many initiatives are now aimed to design parts right the first time in order to avoid those costly changes that can occur later in the design and manufacturing process.

Many aerospace companies are now returning to the time when design integration was easier due to the project simplicity and few engineers could meet and discuss together the relevant parts of an entire project. As the companies grew and the projects became more and more complex, that level of integration was lost. Now they are trying to regain a good level of integration by exploiting the tools provided by information technology.

Computer-Aided Design has been playing a key role in this innovative process during the past few years. The most outstanding example comes from the use of three-dimensional CAD models instead of the traditional physical mock-ups in the design of the structure and the on-board systems of aircrafts (9) (10) (11). Mock-ups have always been part of airplane design and production in Alenia. Engineering has been using them to develop and verify the design before the release of production drawings and to check it for accessibility, maintainability, etc. Manufacturing has been using them as an aid to initiate and verify production.

The problem with physical mock-ups is that they are very hard to build and modify and the time lag necessary to develop them and produce paper drawings can be very long, especially when significant changes occur downstream in the process. The most visible improvement given by the introduction of a digital mock-up is the reduction of this time lag. CAD drawings are available as soon as the models are designed and design changes can be dealt with more easily. Modifying a CAD model is much faster than rebuilding a physical one. Furthermore, the digital mock-up is supported by a network installation of CAD stations. This can give to all parties intervening in the design process instant access to the same models by allowing them to solve possible conflicts and to detect possible sources of design errors very early in the process. Thus, not only a digital mock-up makes it easier to deal with engineering changes, but it can significantly reduce them by helping engineers to detect earlier possible sources of design errors.

In this context of increasing integration of the design and manufacturing process, Artificial Intelligence and knowledge-based systems can play a crucial role. What is new in this technology is that it can represent and use knowledge in a deeper and more direct way than traditional information technology. This paves the way for new applications for modeling and supporting the product design process. In most companies knowledge about designing and manufacturing is usually scattered through the organization and can be found in individual experience, reports, diagrams, drawings etc. Knowledge-based systems can play the role of repositories of some of the company knowledge. This is not to say that all the processes can be modeled by expert systems, neither does this mean that bottlenecks caused by the unavailability of key expert engineers can be totally eliminated. However it is quite natural that knowledge-based systems, while supporting some specific phase of design or manufacturing, can become useful tools to capture part of the company knowledge.

The aim of this paper is to describe how the introduction of a knowledge-based system supporting electrical design may also affect the electrical design process. The system we present is ALEX (Automatic Loom EXpert). It is currently being developed in Alenia, where attentive studies are also devoted to its introduction in the design process.

The paper proceeds as follows: Firstly we briefly describe the task of designing an aircraft electrical system. Next we list a series of design issues that could be affected by knowledge-based systems. Then we present ALEX and its AI methods and finally we discuss how it can improve this design process.

2. Designing an aircraft electrical system

The electrical system is basically made up of equipments, wires and other electrical components such as relays, splices etc. Its basic function is to assure that all the electrically controlled aircraft systems work appropriately both in normal conditions and in some predefined failure cases. Designers provide the critical systems with redundant equipments. Thus a failure to the electrical connections of one of them should not cause a failure of the others. Similarly electrical links carrying a warning signal should not be cut off even though the related equipment can no longer be controlled.

The first input of the process are the functional specifications of the on-board aircraft systems, which specify their main equipments and their basic electrical connections. The design process can be divided in two subtasks which lead to the following outputs:

1) Functional diagrams

2) Wire diagrams and installation drawings

2.1 Functional diagrams

In this phase specifications are transformed in functional diagrams. For each functional connection engineers specify the required number of electrical links and electrical components, i.e. relays, switches, equipment connectors etc.. For each electrical connection they work out the wire size, type (twisted, screened, etc.), EMC (Electromagnetic Compatibility) classification, etc.

In Alenia functional diagrams are drawn using a 2D CAD system. Features can be explicitly associated to the electrical components and then used for consistency checks and design reports. This makes it possible to produce automatically a final output that is both graphical and descriptive.

The main goal is to design these diagrams so as to implement the original system design principles and to get the equipments to work appropriately in all the expected conditions.

2.2 Wire diagrams and installation drawings

In this phase engineers define the wire composition of routings, bundles, bulkheads and bulkhead connectors and their actual location in the aircraft mock-up. Routings represent the main wire routes on the aircraft structure. Wires following each main route are then grouped in bundles. Bulkhead connectors are special connectors that cut wires to get them to pass through bulkheads located on the interfaces between different aircraft sections.

Wire composition of these items is designed by taking into account different and sometimes conflicting requirements. Safety, vulnerability and EMC requirements constrain some wires to be detached from others, i.e., to be distributed either in different routings and bulkheads or in different bundles and bulkhead connectors. Routings should never cross and should keep a distance of at least 500 mm from each other, while for bundles it is required a distance of only 75 mm. On the other hand, regard for assembly and maintainability issues would recommend to keep wires in the same items as long as they have at least one common connector or the equipments they connect are closely located in the aircraft mock-up.

Wire composition of bundles and bulkhead connectors is currently worked out by the Electrical Design Department into the wire diagrams. While the Electrical Design Department produces wire diagrams, the On-Board System Installation Department works out the installation drawings by locating electrical bundles and bulkhead connectors in the aircraft mock-up.

As one can see, these tasks are highly intertwined. In order to distribute wires it is very important to know about equipment locations and the available space in the aircraft mock-up. On the other hand it is not feasible to locate wires in the structural model when bundles have not yet been composed. In this phase it is therefore required a frequent information exchange between the two departments. The task of designing electrical bundles is in turn part of the general task of installing the on-board systems on the aircraft mock-up. Here electrical requirements may be in conflict with the requirements of other systems (e.g. hydraulic, fuel, etc.) and with space and structural constraints.

Thanks to the introduction of the digital mock-up, the installation drawings of the electrical bundles have been released much earlier than before. This has improved the design quality of the electrical system. Delays have been reduced and, as far as space is concerned, its requirements have been satisfied in a better way. Still, it is quite clear that the electrical design process could be more integrated in itself. In particular we think that the following issues still need to be addressed:

1) Control of information flow. As we saw, the main goal is to satisfy the basic system requirement specifications. These may change over time and frequent and unexpected modifications may complicate the design process. Thus it is essential to control the information flow and to trace back the basic

design choices to the requirements that justify them.

2) Integration of wiring and installation phases. The tasks of defining bundle composition and installation are highly intertwined. The introduction of the digital mock-up speeds up the installation phase. However, engineers who work out the bundle installation models do not have direct access to their wire composition. At the same time engineers designing wiring diagrams use the installation models only to get the resulting length of the bundles.

3) Integration of the electrical system installation with the other on-board systems. So far as this issue is concerned, the introduction of the digital mock-up has opened a new perspective. However, the number and the appropriate size of the main routings necessary to satisfy the electrical requirements should already be available in the first phase of the aircraft design, the so-called definition phase, so as to constrain the installation of the other on-board systems.

In the following we will describe ALEX and the methods it uses to tackle these issues.

3. Description of ALEX

ALEX is a knowledge-based expert system whose basic role is to support engineers in the second subtask of the design process. It takes as input wire and equipment features drawn out of functional diagrams and the 3D digital models of the aircraft structure. ALEX role is twofold: It provides the minimum number of main routings, bundles, bulkheads and bulkhead connectors and their wire composition. In addition, it is connected with a CAD station to automatically draw preliminary wire routes in the aircraft mock-up model.

Work on ALEX began in early 1990 with an analysis of the electrical design process and the AI methods suitable for supporting it. Now it is in an advanced development phase. The first version of the system has been used in Alenia since 1993 by working on the main programs of the company.

ALEX solves different problems with different methods and it is a good example of the complexity of design viewed as a knowledge-based problem solving activity. It applies rules, constraint satisfaction methods and search algorithms in combination with complex domain heuristics. ALEX has been implemented in Common Lisp and runs on a Sparc station SUN. It is connected to a CAD system (CADDS) running on another Sparc station SUN through the Ethernet network and the Unix Inter Process Communication (IPC). Now we will describe ALEX process and its AI methods by following the steps displayed in figure 1.

Tasks	**AI Methods**
Wire Tables	Production rules
Routings	
Bulkheads	Constraint Satisfaction Algorithms
Bulkhead connectors	Wire Assignment Heuristics
Bundles	
Routing Installation	Search Algorithm

Fig. 1 - Tasks performed by ALEX and corresponding AI methods

3.1 Wire tables

In order to define the wire composition of routings, bundles, bulkheads and bulkhead connectors we chose the constraint satisfaction and propagation methods combined with specific domain heuristics. Here constraints represent system and electrical requirements to keep wires detached from each other, either divided (different routing and bulkhead) or separated (different bundle and bulkhead connector), However constraints are not explicitly stated in the functional diagrams. Thus the first subtask accomplished by ALEX is to bring about explicit constraints. This is done by exploiting a set of production rules representing the design knowledge involved in this task.

ALEX comes out with constraint matrices, or **wire tables**, where all the division and separation requirements are explicitly stated for each wire (see fig. 2). The following rules belong to the general rule class and apply to any on-board system:

IF *the equipment A is redundant of the equipment B*

THEN divide A's wires from B's wires

IF *X is a warning wire of equipment A*
Y is a command wire of equipment A

THEN divide X and Y

These wire tables are the input data of the successive tasks performed by ALEX. Moreover they may be exploited by engineers to check the electrical design consistency up to this point. Since each constraint may be explained by the rule producing it, it will be possible to trace back to the original requirement any design choice concerning wire division and separation.

3.2 Routings, Bulkheads, Bulkhead Connectors and Bundles

Wire table constraints are exploited to determine the minimum number and wire composition of routings, bulkheads, bulkhead connectors and bundles. The design of these items is formalized as a series of constraint satisfaction problems (from now on CSPs) as follows:

- Variables $X_1, X_2, \ldots X_n$ represent wires
- Domains $D_1, D_2, \ldots D_n$ containing values possibly assigned to variables are sets of routings, bundles, bulkheads or bulkhead connectors depending on which item is being designed.
- Constraints $C_1, C_2, \ldots C_k$ define wire compatibilities and are represented by the wire tables

Solving these CSPs means finding an assignment of a domain value to all wires such that all the related constraints are satisfied (for a general introduction to CSPs, see (1) (2) (4)). Each CSP is solved by means of a depth-first search using the so-called backjumping strategy (3). This is a variant of conventional backtracking that takes advantage of the search space structure to reduce the amount of node expansions necessary to find a solution or to realize that a solution can not be found. It is based on the idea that when a dead end occurs, i.e., no value can be assigned to the current variable, it is useless to backtrack to variables which are not constrained by the current one. Thus the algorithm may jump back to the most recent variable constrained by it without losing any possible solution.

In this application the number of domain values, i.e. electrical items, for each variable is not given *a priori*, but should be the minimum number that satisfies all the constraints. For any given set of domains, solutions of different design quality may be found. Even though they all satisfy the system requirements, some of them may be better from the assembly point of view. This is the case, for instance, when most of the wires departing from the same connector are kept in the same routing. Since it is not feasible for computational reasons to explore the whole tree and generate all the solutions, search is heuristically guided so as to get a trade-off solution of good design quality. The algorithm stops as soon as it finds a solution, while heuristics drive it by altering the variable order and the value assignments.

Thanks to these heuristics, the solution which ALEX provides takes into account not only design constraints, but also assembly and maintainability criteria. It is unlikely that this could be the perfect solution from any point of view. However ALEX contribution can not be neglected: It provides a preliminary configuration satisfying the basic design and assembly requirements as soon as the basic wire and equipment data are available. This allows the designers to avoid many conflicts that would have occurred downstream. Moreover, even though wire and equipment data are not complete, CSPs can provide the minimum number and size of the main routings necessary to satisfy the electrical requirements. Engineers have therefore the opportunity to determine the installation requirements of the electrical system already in the definition phase of the aircraft design.

3.3 Routing Installation

The next step performed by ALEX is to install the main routings in the digital mock-up model. Its goal is to keep them at a distance of at least 500 mm and optimize various criteria such as path simplicity, number of holes in the structure and accessibility.

The aircraft mock-up is represented by a 3D CAD model. Its simplest version, called **key diagram**, is a model of the aircraft structure represented without thickness.

A basic difference between CAD and knowledge-based systems is that the former manage only geometric design information, while the latter capture in some way the intent behind the product design. It is clear that systems that use only graphical data are limited in their ability to automate the design and engineering process, since they provide no means of capturing the engineering expertise behind the design [6] [7] [8]. Knowledge-based engineering may complement computer-aided design in two ways:

- Models designed on a CAD system may be used as geometric constraints by a knowledge-based design system.
- Once the knowledge-based system has generated either a design instance or a new part in the same model, geometry may be automatically transferred to the CAD system in order to complete the design and produce detailed drawings.

The original key-diagram which defines the physical structure of the aircraft and the location of the main equipments is the ALEX geometric input provided by the CAD system. Once ALEX has processed these geometric data, the installation of the required routings and their equipment connections are transferred back into the key-diagram model. This installation is preliminary. It is not the final solution because some constraints may still be unknown up to this point. The generated CAD model will be further adjusted, modified and detailed with the usual CAD facilities.

The original key-diagram is a wire-frame model made up of points and curves. Features associated to points define the topological areas (bays and zones) and the structural parts (frames, longerons and ribs). ALEX processes features and geometric data so as to apply an AI method, i.e. a search algorithm, suitable to generate a routing configuration satisfying the basic installation requirements and the other heuristic criteria. As one can see in fig. 2, in order to define the paths of the wire routings it needs two intermediate models:

1. Object model
2. Graph model

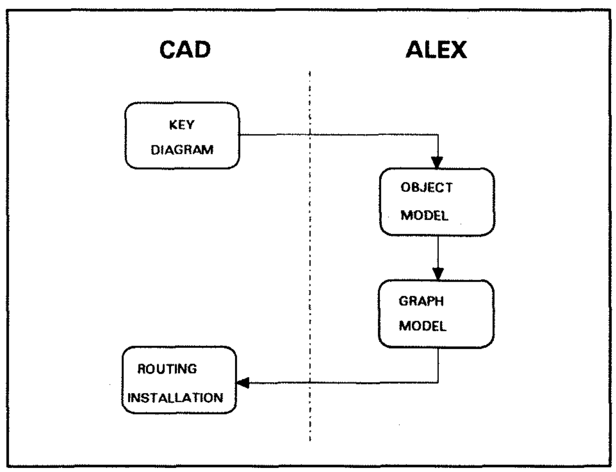

Fig. 2 - Information flow in the CAD - ALEX interaction

3.3.1 The object model

The object model is an object-oriented data base representing the aircraft mock-up on the ALEX side and including the following information:

a. Objects representing structural parts and topological areas of the aircraft. Associated information includes point coordinates and qualitative features such as bay accessibility, frame type etc. This part of the object model is automatically created by processing information coming from the CAD system.

b. Information generated by the knowledge-based system itself such as routing locations, new holes to make the routings pass through structural parts etc. As ALEX draws routings on the wire-frame model, the object model is updated so as to keep it coherent.

3.3.2 The graph model

After the object model has been created, the system builds up a graph model to represent alternative paths. The nodes of the graph stand for the vertices of the accessible bays, while the arcs represent the structural parts which connect them. There are two ways to get through an arc, either by passing over a structural part or by passing through it to get another bay. Given start and end points, ALEX uses a traditional best-first search algorithm to find the best solution through the graph. The cost function exploits criteria such as path length, bay accessibility, number of holes, locations of already installed routings etc.

The solution paths consist of legs, each defined by a structural part, the corresponding bay and a feature which points out whether the path passes over the structural part or through it. Thus the initial part of a routing path may be represented as follows: [(frame-101, bay-411, over), (long-upper, bay-411/bay-451, through), (frame-101, bay-451, over), ...]. Once paths have been found, a drawing algorithm, which interprets the result of the graph search, draws them on the wire-frame model by converting the symbolic paths in geometric data.

3.3.3 The drawing algorithm

This algorithm exploits the existing connection between ALEX and the CAD system to draw the wire routings and to get on the CAD model the geometric data coming out of the knowledge-based processing. The result is a detailed geometric counterpart of the generic path outlined by the search algorithm (see fig. 3). The actual drawing is performed by transferring CAD command files to the CAD workstation in order to get them executed. Moreover ALEX may require interference checks with the structure to the CAD system and get the answer back. The algorithm calls the installation methods associated to each structural part of the object model and, leg by leg, determines the actual coordinate points of the routing paths. Structural parts resulting from the graph search are therefore installed on the mock-up model according to their characteristics.

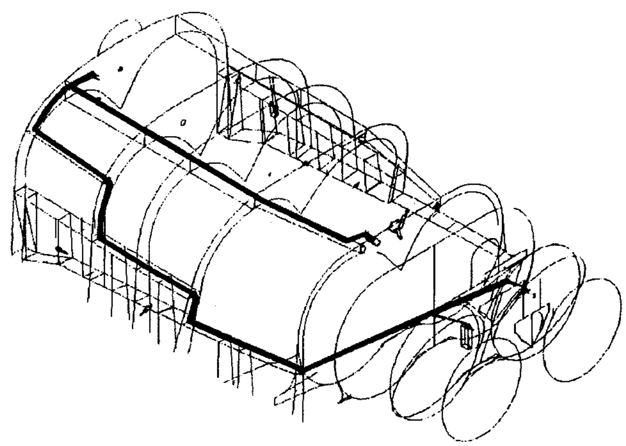

Fig. 3 - Two routing paths drawn by ALEX in a key-diagram model. Paths have been filled to make them visible.

How can this kind of interaction between ALEX and the CAD system affect the electrical design process? First of all, designers installing the electrical system have access to a preliminary configuration that takes into account the basic system and assembly requirements. The electrical items defined by ALEX in the previous steps incorporate these requirements and, thanks to this interaction, make them available in the CAD environment. The most outstanding consequence of this integration is that the available information concerning the current design solution is no longer scattered throughout the company, but it is concentrated in ALEX. Any mistake and possible misunderstanding may be solved quickly, because it is not necessary to go through various departments to get the relevant information.

4. Conclusion

In this paper we have briefly described the task of designing an aircraft electrical system. We have also presented ALEX, a knowledge-based system supporting a few phases of the electrical design process. We have seen that ALEX could help the engineers to produce a better electrical configuration in a shorter time. This is partly due to its effective integration of a few parts of the design process.

The ALEX - CAD interaction allows to integrate the activities concerning the design of the wire diagrams and the installation drawings. The combination of constraint satisfaction methods and domain heuristics takes into account both system specifications and assembly and maintenance constraints. Furthermore, CSP algorithms can determine how many routings are needed to satisfy the electrical requirements even though wires and equipment data are not yet available. Finally the automatic generation of wire tables and the use of explanation mechanisms permit to trace back the table constraints to the corresponding requirements.

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