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NASA Technical Memorandum 85919

NASA-TM-85919 19860014132

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February 1986

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N86-23603 #

SUMMARY

Expert system techniques, a major application area of artificial intelligence (AI), are examined in the development of a pilot associate to handle aircraft emergency procedures. The term "pilot associate" is used to describe research involving expert systems that can assist the pilot in the cockpit. The development of expert systems for the electrical system and flight control system emergency procedures are discussed. A simple, high-level expert system provides the means to choose which knowledge domain is needed. The expert systems were developed on a low-cost, FORTH-based package, using a personal computer.

INTRODUCTION

Project Background

The increasing complexity of fighter aircraft is adding to the pilot workload. For example, during in-flight emergencies, the time available to take appropriate action can be limited, and the resulting pilot workload can be extremely demanding. An approach to reducing the pilot workload involves the development of a pilot associate using expert system technologies.

This paper describes the results of a simple expert system development project for an advanced fighter aircraft. The goals of the research are as follows:

1. To obtain a basic understanding of AI and the techniques used in expert systems.

2. To obtain an understanding of the considerations required to develop an expert system for use in a critical application such as the pilot associate.

3. To provide a simple expert system that can be operated on a widely available personal computer and that will demonstrate some capabilities of the technology.

Three expert systems were developed to assist the pilot in emergencies. The expert systems included the electrical system failure procedures (ELECXPRT), the flight control system failure procedures (DFCSXPRT), and a third expert system (supervisor XPRT) to choose the appropriate knowledge domain. The expert systems were developed and run on a personal computer. The work was performed by a high school senior, with engineering assistance, under the Summer High School Apprenticeship Research Program (SHARP) during the summer of 1984.

Background on Artificial Intelligence

AI is a specialized field of computer science which concentrates on making computers "smarter." Hence, AI programs are capable of making deductions, inferences, and conclusions by evaluating the current or input problem state. This evaluation is based upon and guided by a knowledge base of known facts, rules, and procedures (refs. 1 to 3).

Four basic elements of AI are heuristic search, knowledge representation, commonsense reasoning and logic, and AI languages and tools.

The first element, heuristic search, is a search process used by the program to reach its conclusion. Early AI programs used blind (unguided) search methods. This tended to be inefficient and time-consuming. The problem worsened as the knowledge base was expanded to cover a larger domain. To combat this problem, heuristic search procedures were developed. The search process is quided by a special set of rules or instructions that narrow the search area and reduce solution time by guiding the search away from unfruitful solution paths.

Knowledge representation, a popular area in current AI research, is concerned with structuring a knowledge base so that it is both efficient and easily expandable.

The third area mentioned, commonsense reasoning and logic, is one of the most challenging in AI today. "Common sense" is believed to be low-level reasoning based on vast experience. The problem facing many AI researchers today is how to produce a system that learns what to anticipate as the result of an action. A similar concern is formulating how to deduce something from a large set of facts.

The last element of AI is that of special languages and tools needed for intelligent applications. Because of the nature of AI, conventional languages such as FORTRAN and BASIC, do not provide the performance capabilities necessary for AI applications. For this reason, a new generation of computer languages was developed. The two most widely used are LISP and PROLOG. Nevertheless, the basic techniques used by AI programs are based on conventional mathematics: predicate calculus, logic, and proofs.

There are also four major areas of AI applications: natural language processing (NLP), computer vision, expert systems, and general problem-solving and planning.

NLP focuses on developing systems with computer-based speech understanding, text understanding, and the generating of speech and text.

Computer vision involves enabling a computer to "see", to identify or understand what it sees, or to locate particular items.

Expert systems research concentrates on making a computer perform as if it were an expert in a specific domain. The primary goal is to develop a system which can solve problems with at least the same speed and quality as a human expert in that field.

In general problem-solving and planning, the emphasis is on developing systems to solve problems for which there are no known human experts. In many cases, the solution and planning techniques learned in the development process are as important as the final product.

These aspects of AI programming distinquish it from conventional programming. The major differences between the two are listed in table 1.

NOMENCLATURE

AFTI	advanced fighter technology integration
AI	artificial intelligence
BATT FAIL	battery failure
DFCS	digital flight control system
DFCSXPRT	digital flight control system expert
ELEC SYS	electrical system
ELECXPRT	electrical system expert
EPU	emergency power unit
EXPERT-2	title of expert system development tool
FC FAIL	flight control failure
FLT CONTL SYS	flight control system
FORTH	fourth-generation programming language
IBU	independent backup unit
MAIN GEN	main generator
MPD	multipurpose display
NLP	natural language processing
PMG	permanent magnetic generator
SHARP	summer high school apprentice research program
XPRT	high-level expert system
Δp	change in pressure

EXPERT SYSTEMS

The research project at the Dryden Flight Research Facility of the NASA Ames Research Center (Ames-Dryden) focused on a specific area of AI, the expert system. The typical expert system is divided into three distinct parts: the knowledge base, the control structure, and the global data base (fig. 1). The knowledge base contains the domain knowledge, usually in the form of rules, that the expert uses to reach its conclusion. A special set of inference rules to be used for determining heuristic search patterns may also be included in the knowledge base. The control structure contains the center of the system, the rule interpreter, which is also called the inference machine or inference interpreter. The inference machine utilizes the rules found in the knowledge base to reach its conclusion. The inference machine also uses any applicable inference rules, in addition to any heuristics programmed into the control structure itself, to guide its search. The final segment of the expert system structure is the global data base where the system status is stored. The present state, the goal state, the initial state, and any deductions or inferences made by the interpreter are typical data which may be contained in the global data base.

The specific expert system used in this project was a modified version of the EXPERT-2 system and is a FORTH-based program (refs. 4 and 5). This expert system is similar in structure to the basic system described previously. The primary difference between the EXPERT-2 global system and a generic expert system is the data base. The EXPERT-2 program simply maintains, as its data base, two stacks that contain a list of statements known to be true and a list of statements known to be false.

SYSTEM IMPLEMENTATION

The expert systems developed are based on the advanced fighter technology integration (AFTI) F-16 aircraft used in research at Ames-Dryden. The AFTI F-16 airplane is a highly modified F-16 used in a joint U.S. Air Force and NASA program to demonstrate the capabilities of various nonconventional flight modes. AFTI uses a three-computer digital flight control system with no mechanical backups. The electrical and flight control systems described in this report are unique to the AFTI F-16 aircraft.

Electrical System Expert

The first expert system, electrical system expert (ELECXPRT), was designed to diagnose AFTI F-16 electrical system failures. The initial step toward implementation was to gain an understanding of the operation of the aircraft electrical system.

Electrical power is supplied by a primary generator, an emergency generator which is part of the emergency power unit, and two batteries. In case of a primary generator failure, backup power is provided by the emergency power unit (EPU), which is powered by bleed air from the engine. If bleed air is not sufficient, EPU operation is augmented by hydrazine fuel.

The EPU consists of an emergency generator and a permanent magnetic generator (PMG). If the emergency generator fails, reduced power is still supplied by the PMG. In case of a total generator failure, the aircraft can still be powered by either of the two batteries.

The ELECXPRT uses as its inputs the same failure indications given to the pilot: a MAIN GEN failure light, an EMER GEN failure light, an EPU RUN light, a BATT FAIL-1 light, and a BATT FAIL-2 light. These inputs are obtained from the user by asking questions on the computer screen. In a real aircraft application, the failure lights would be monitored.

The knowledge base was derived from the AFTI flight manual. From these data, the ELECXPRT determines the proper emergency procedures to be followed and displays this information to the user.

In some instances, the ELECXPRT prompts the user for more information regarding the failure state, and gives the subsequent procedural information according to these responses.

The rule base, which the ELECXPRT uses to make its conclusions, was compiled from the same procedural information in the AFTI flight manual (ref. 6) used by the pilot (fig. 2).

Digital Flight Control System Expert

The DFCS provides control of the aircraft through its three digital computers; there are only electrical links to the control-surface hydraulic actuators. The DFCS and its interfaces to the aircrafts sensors, controllers, and control surface actuators are shown in figure 3.

An analog independent backup unit (IBU) is implemented in each of the three digital computers. These three IBUs provide safe operation of the aircraft in the event of a common mode failure of the three primary digital computers.

The DFCS has the ability to identify failures in any component (sensors, computers, or actuators) for each of its three channels. The fault indications given to the pilot include cockpit failure lights and a message printed on the cockpit multipurpose display (MPD). The MPD gives detailed information regarding which DFCS component has failed, how many have failed, and which aircraft control axes are affected.

The DFCSXPRT uses as its input the DUAL FC FAIL light, the IBU light, the first line of the MPD fault page, and the device identification (DID) number displayed on the second line of the MPD. Again the information is obtained by posing them as questions to the user. As with the ELECXPRT, the DFCSXPRT provides the user with emergency procedures to be followed in a given failure state and occasionally requests additional information. Some of the procedural information, taken from the flight manual, is given in figure 4.

In addition to the expert system itself, a special user interface was designed for the DFCSXPRT. This routine employs information from the user to determine the truth value of a special set of rules before control is passed to the inference machine. This capability allows MPD text to be entered into the DFCSXPRT in addition to answering the yes-and-no questions presented by it.

Supervisor Expert

After development of ELECXPRT and DFCSXPRT, a third expert program supervisor XPRT was written. This is an expert program which oversees the other two expert systems (fig. 5). It decides whether ELECXPRT or DFCSXPRT is better equipped to handle the fault diagnosis. This determination is based on the evaluation of the MASTER CAUTION, FLT CONTL SYS, IBU, and ELEC SYS lights. The supervisor XPRT was designed so that future expert programs could be incorporated by adding the necessary rules and routines for accessing such programs.

In designing the expert systems, it was necessary to account for inconsistencies and highly unlikely failure conditions which were not specifically discussed in the AFTI flight manual. Evaluation of such conditions resulted in a more extensive list of possible failures and proper emergency procedures. An expert system is of particular value in such situations. An expert can give the pilot information regarding conditions not specifically covered by the flight manual, which could mean the difference between a possible solution and further deterioration of a failure state.

DISCUSSION

Three major observations should be mentioned. They concern knowledge engineering, the interfacing of an expert system to the aircraft system, and qualifying the expert system.

Knowledge engineering is the gathering of the facts for the expert system and compiling them into a form suitable for the inference machine. For example, three iterations of the rule base for the electrical system occurred during its development. The primary reasons were to become familiarized with the expert systems format and to understand the electrical system. The rules to cover rare failure conditions that were not provided in the flight manual resulted in one of the iterations. The ELECXPRT was designed to cover all possible failure-light conditions.

Interfacing the expert to the aircraft systems is discussed from more of a functional aspect than a physical one. Using the ELECXPRT as an example, three levels of system abstraction may be defined. The first is raw data such as the voltage output level of the primary generator. From this, the next level of abstraction — information — is obtained. For instance, the information could be that the primary generator has failed and would be derived from a combination of raw data and the knowledge of the designer.

The third level of abstraction is more difficult to catagorize but could be called performance. Performance is derived from the knowledge of the aircraft system as a whole. For example, with a primary generator failure, the performance or capability of the aircraft can be derived by certain expert knowledge. The pilot procedures also are derived by this knowledge. The expert system described here contains the knowledge to develop the third level of abstraction (performance) from the second level of abstraction (information). It is not based on any raw data and assumes that the knowledge given by the designer is correct. The procedures give resulting performance capability; for instance, that only 15 min of aircraft control remain or that the amount of remaining battery time is low.

Although the ELECXPRT is a very simple example, it raises the question of how extensive the knowledge of an expert system must be to assure accurate results. With a DFCS, this becomes a trade-off between the knowledge designed for storage in the expert system and the knowledge designed into the digital flight control system using conventional techniques. For example it is necessary to know what role should an expert system have when detecting, and reconfiguring for failures.

The problem of qualifying large expert systems for proper operation is another major concern. The approach used here is the same as that for the software qualification of flight-critical control system software. Each of the experts is small enough in its domain of knowledge so that it can be accurately qualified. The individual experts must then be integrated together and qualified as a whole. The qualification for the ELECXPRT, for example, required 54 test conditions. In each test, the expected results were identified before the test was run. The test results were then compared with the expected results. The final step in the production of the XPRT system was this software verification.

CONCLUDING REMARKS

An overview of the field of artificial intelligence (AI) was obtained. The goal to acquire a basic understanding of the concepts behind expert systems and their applications was also accomplished. Three expert systems were developed on a personal computer to assist an aircraft pilot in cases of emergency. These systems included one for electrical failure procedures, another for flight control system failure, and a third to oversee or supervise the choosing of the appropriate knowledge domain. The electrical system expert (ELECXPRT) was capable of handling all possible failure conditions and qualified completely. The DFCS expert (DFCSXPRT) was capable of handling both binary yes-and-no cases and text strings to determine proper pilot procedures. The expert system also provides emergency procedures for low-probability failure conditions that are not covered by the flight manual (ref. 6).

Applying the expert system technology to a simple pilot associate provided hands-on experience essential for good understanding. It is hoped that this expert system will demonstrate the value of a real-time application of expert system technology in a flight environment.

Ames Research Center
Dryden Flight Research Facility
National Aeronautics and Space Administration
Edwards, California, October 11, 1984

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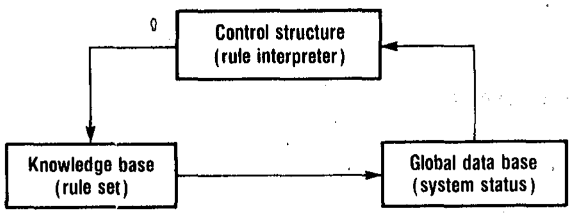
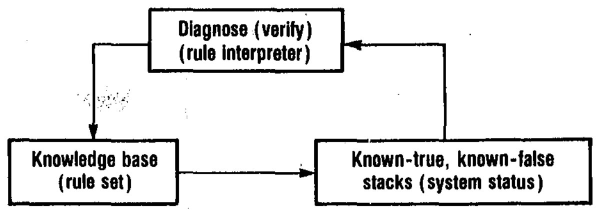
TABLE 1. — COMPARISON OF AI WITH CONVENTIONAL PROGRAMMING

AI Programming	Conventional Programming
Primarily symbolic	Primarily numeric
Heuristic search (solution steps implicit)	Algorithmic (solution steps explicit)
Control structure separate from knowledge domain	Information and control integrated together
Easy to modify, update, and enlarge	Difficult to modify, update, or enlarge



(a) *Basic expert system.*



(b) *EXPERT-2 system.*

Figure 1. Expert system structures.

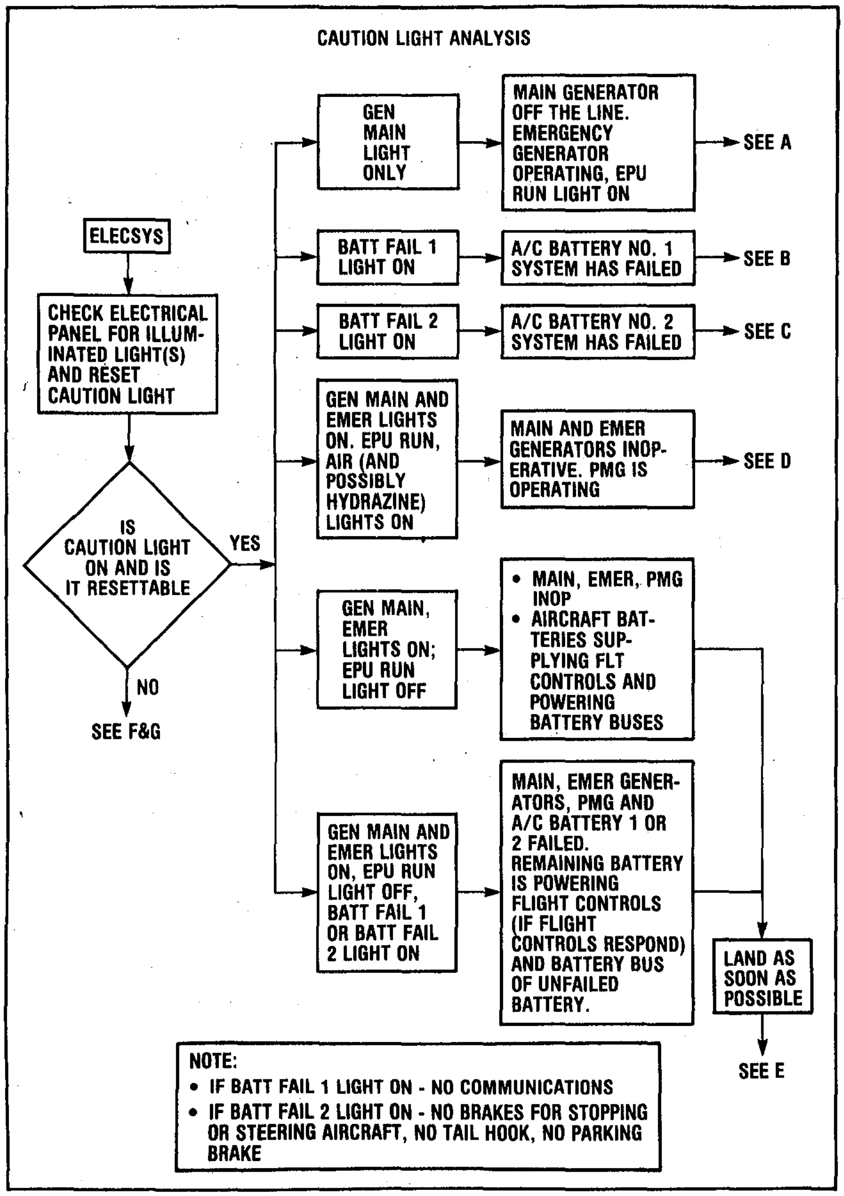


Figure 2. Example of caution-light analysis flow diagram (from ref. 6).

CAUTION LIGHT	CAUSE	CORRECTIVE ACTION/REMARKS
ELEC SYS Check ELEC panel fault lights and reset caution light		
GEN MAIN light	Main generator failure	A. Attempt reset 1. MAIN PWR switch – BATT, then MAIN PWR If main generator resets 2. EPU knob – OFF, then AUTO If main generator does not reset 3. MAIN PWR switch – MAIN PWR (verify) 4. Monitor fuel balance 5. Monitor Hydrazine quantity 6. Land as soon as possible NOTES • GEN MAIN light indicates electrical power to nonessential ac and dc buses lost • EPU furnishes electrical power for both essential ac buses • Refer to MAIN GENERATOR FAILURE
BATT-FAIL 1 light	A/C battery system No. 1 failure	B. 1. EPU knob – ON (When flight conditions permit) Check EPU run light If EPU runs abnormally 2. EPU knob – Cycle to OFF, then AUTO. 3. Land as soon as possible NOTES • Refer to BATTERY SYSTEM FAILURES • Refer to LANDING WITH FIRED EPU
BATT-FAIL 2 light	A/C battery system No. 2 failure	C. Same as B except as noted: NOTE • If main generator also fails, no electrical power available to start EPU.

Figure 2. Continued.

CAUTION LIGHT	CAUSE	CORRECTIVE ACTION/REMARKS
ELEC SYS		
GEN MAIN and GEN EMER lights (EPU RUN light on)	Failure of both main and emergency generators	D. 1. MAIN PWR switch – BATT, then MAIN PWR If main generator resets 2. EPU switch (knob) – OFF, then NORM (AUTO) If main generator does not reset and EPU is on 3. MAIN PWR switch – MAIN PWR (verify) 4. Land as soon as possible NOTES • Only FCS and equipment connected to battery buses will function • PMG operation indicated by EPU RUN light on. • Refer to MAIN AND EMERGENCY GENERATOR FAILURE (PMG OPERATING)
Total Generator Failure GEN MAIN, GEN EMER (EPU RUN LIGHT OFF)		E. Refer to TOTAL GENERATOR FAILURE NOTES • PMG failure indicated by no EPU RUN light.
No ELEC panel fault lights (ground operation)		F. Push CAUTION RESET button on electrical panel • If light stays on with main generator on line – notify maintenance • If light goes off – notify maintenance
Steady ELEC SYS light (not resettable) (EPU RUN LIGHT OFF) (Any combination of ELEC panel fault lights possible)		G. On the ground – notify maintenance; in flight – refer to ABNORMAL EPU OPERATION, this section.

Figure 2. Concluded.

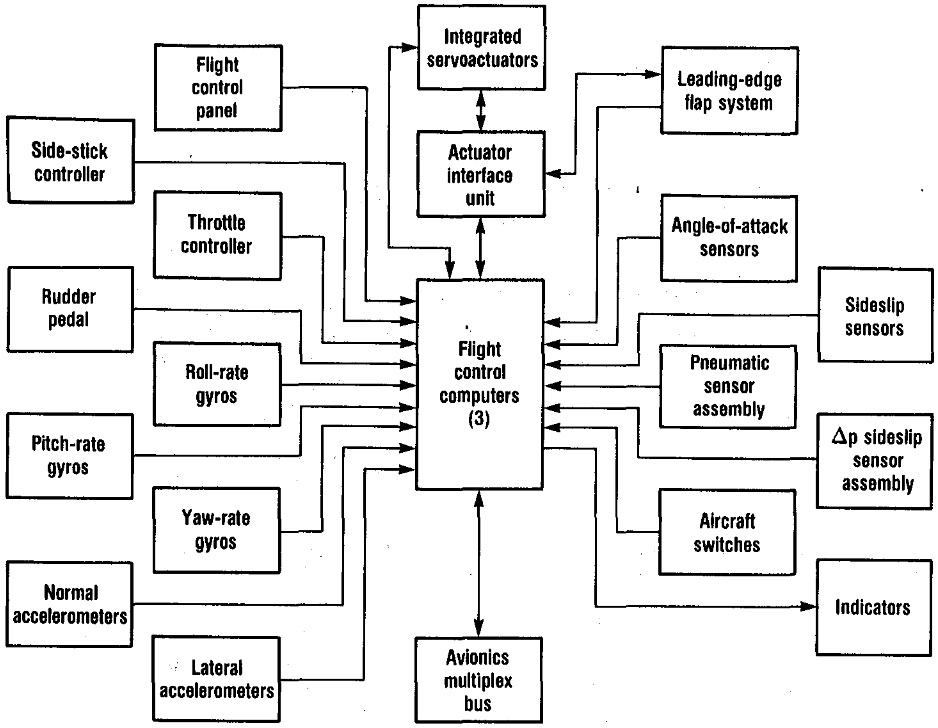


Figure 3. Digital flight control system.

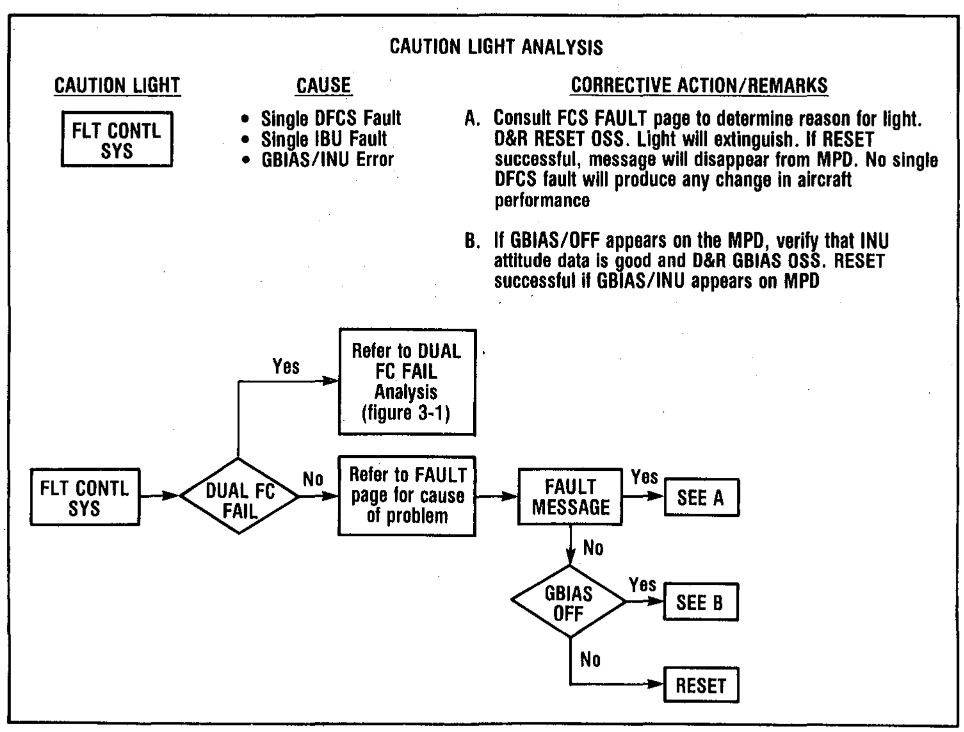


Figure 4. Example of caution-light analysis procedure for flight control system (from ref. 6).

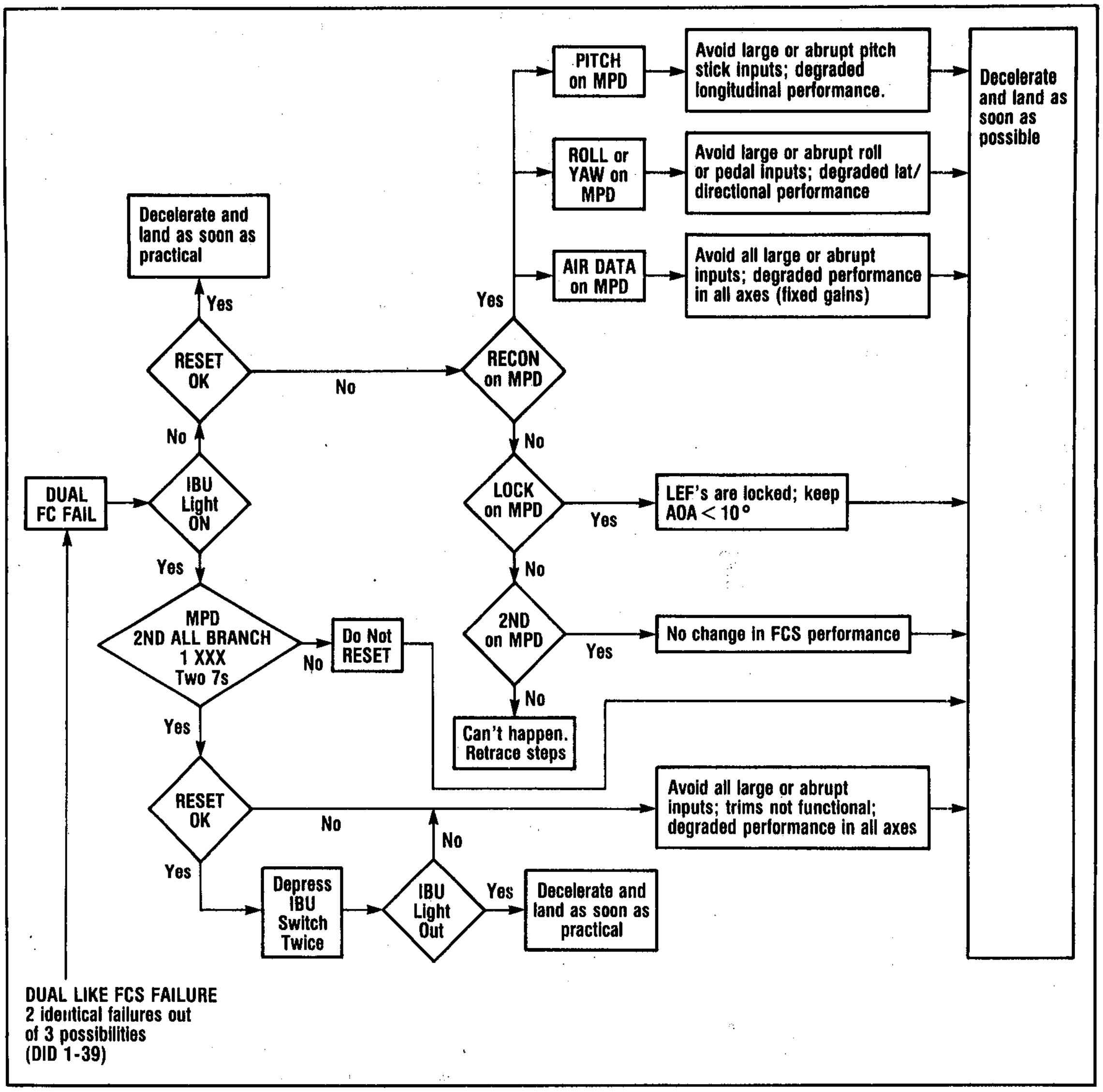


Figure 4. Continued.

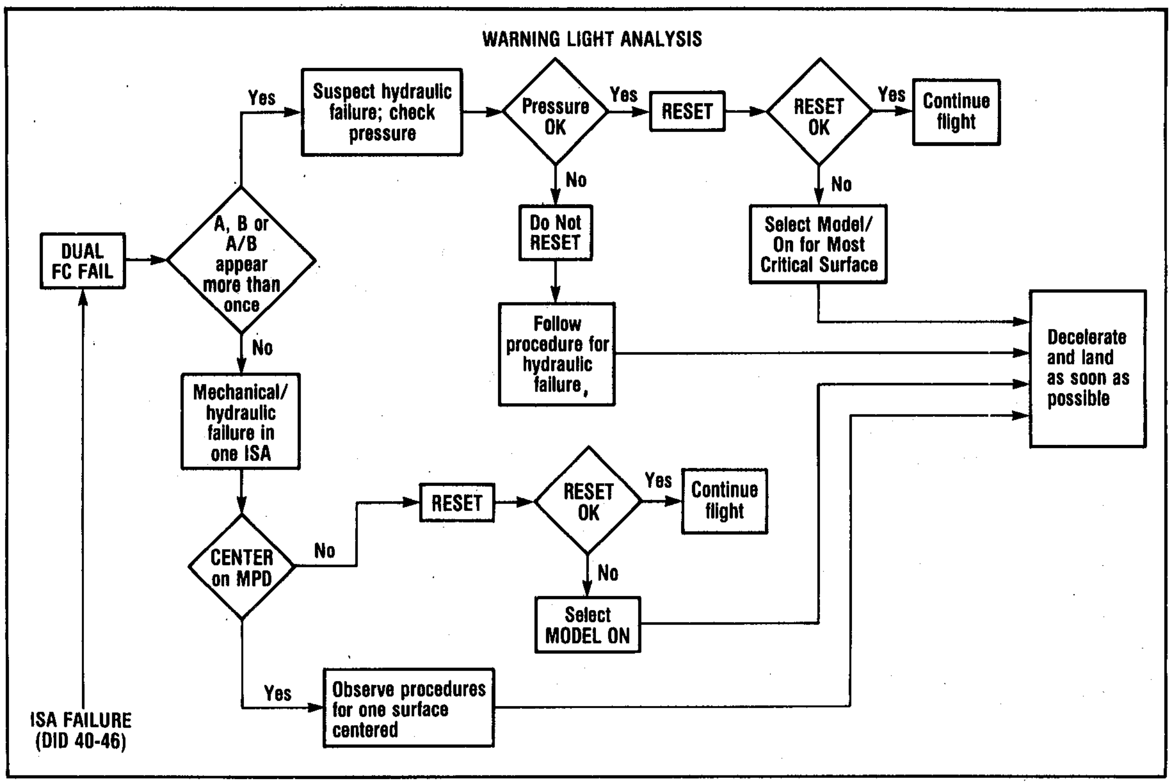


Figure 4. Concluded.

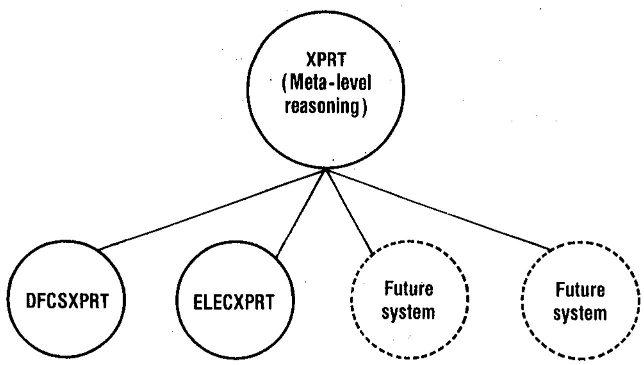


Figure 5. Relationship of three expert systems with potential for future additional expert systems.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-85919		

4. Title and Subtitle	5. Report Date
Development Experience With a Simple Expert System Demonstrator for Pilot Emergency Procedures	February 1986
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Michael Van Norman and Dale A. Mackall	H-1272
	10. Work Unit No. RTOP 533-02-61
9. Performing Organization Name and Address NASA Ames Research Center Dryden Flight Research Facility P.O. Box 273 Edwards, CA 93523-5000	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Aircraft control systems Expert system Pilot associate	Unclassified — Unlimited STAR category 08

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	15	A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161.

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