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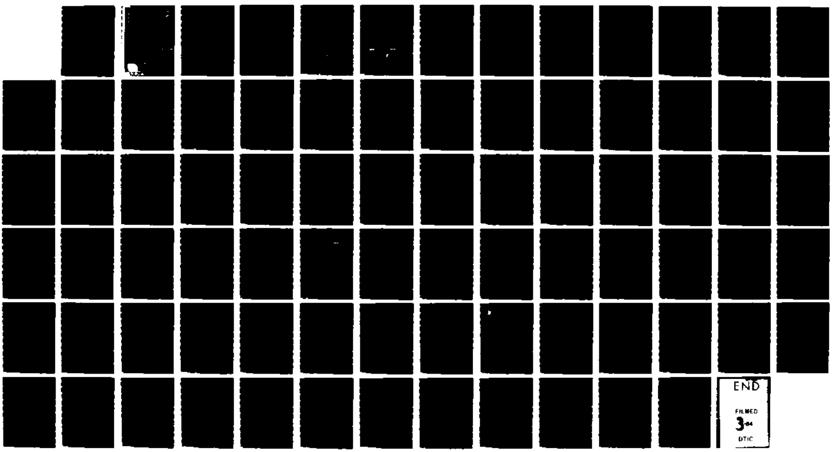

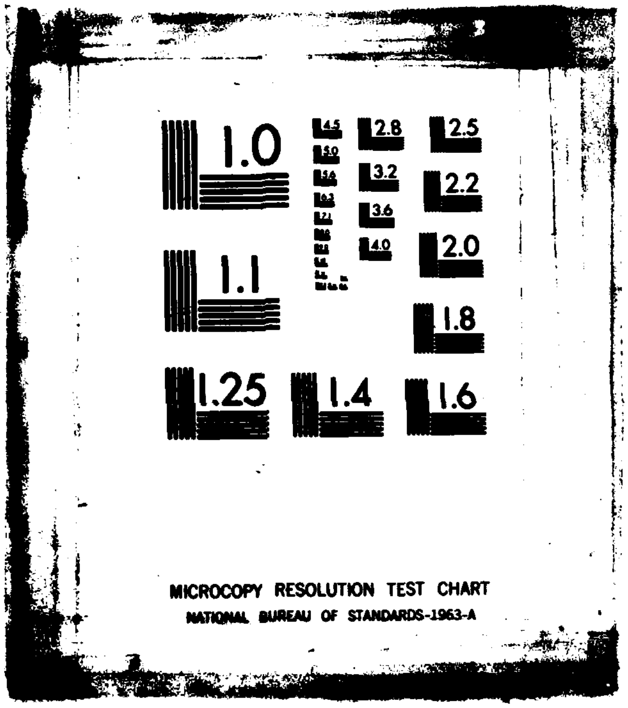
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ARTIFICIAL INTELLIGENCE APPLICATIONS TO MAINTENANCE TECHNOLOGY WORKING GROUP REPORT (IDA/OSD R&M STUDY)

Anthony Coppola, USAF
Working Group Chairman

August 1983

The views expressed within this document are those of the working group only. Publication of this document does not indicate endorsement by IDA, its staff, or its sponsoring agencies.

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Office of the Under Secretary of Defense for Research and Engineering
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(Manpower, Reserve Affairs and Logistics)

INSTITUTE FOR DEFENSE ANALYSES
SCIENCE AND TECHNOLOGY DIVISION

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This document records the activities and presents the findings of the Artificial Intelligence Applications to Maintenance Technology Working Group, part of the IDA/OSD Reliability and Maintainability Study conducted during the period from July 1982 through August 1983.

IDA RECORD DOCUMENT D-28

ARTIFICIAL INTELLIGENCE APPLICATIONS TO MAINTENANCE TECHNOLOGY WORKING GROUP REPORT
(IDA/OSD R&M STUDY)

Anthony Coppola, USAF
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August 1983

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INSTITUTE FOR DEFENSE ANALYSES
SCIENCE AND TECHNOLOGY DIVISION
1801 N. Beauregard Street, Alexandria, Virginia 22311

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RELIABILITY AND MAINTAINABILITY STUDY

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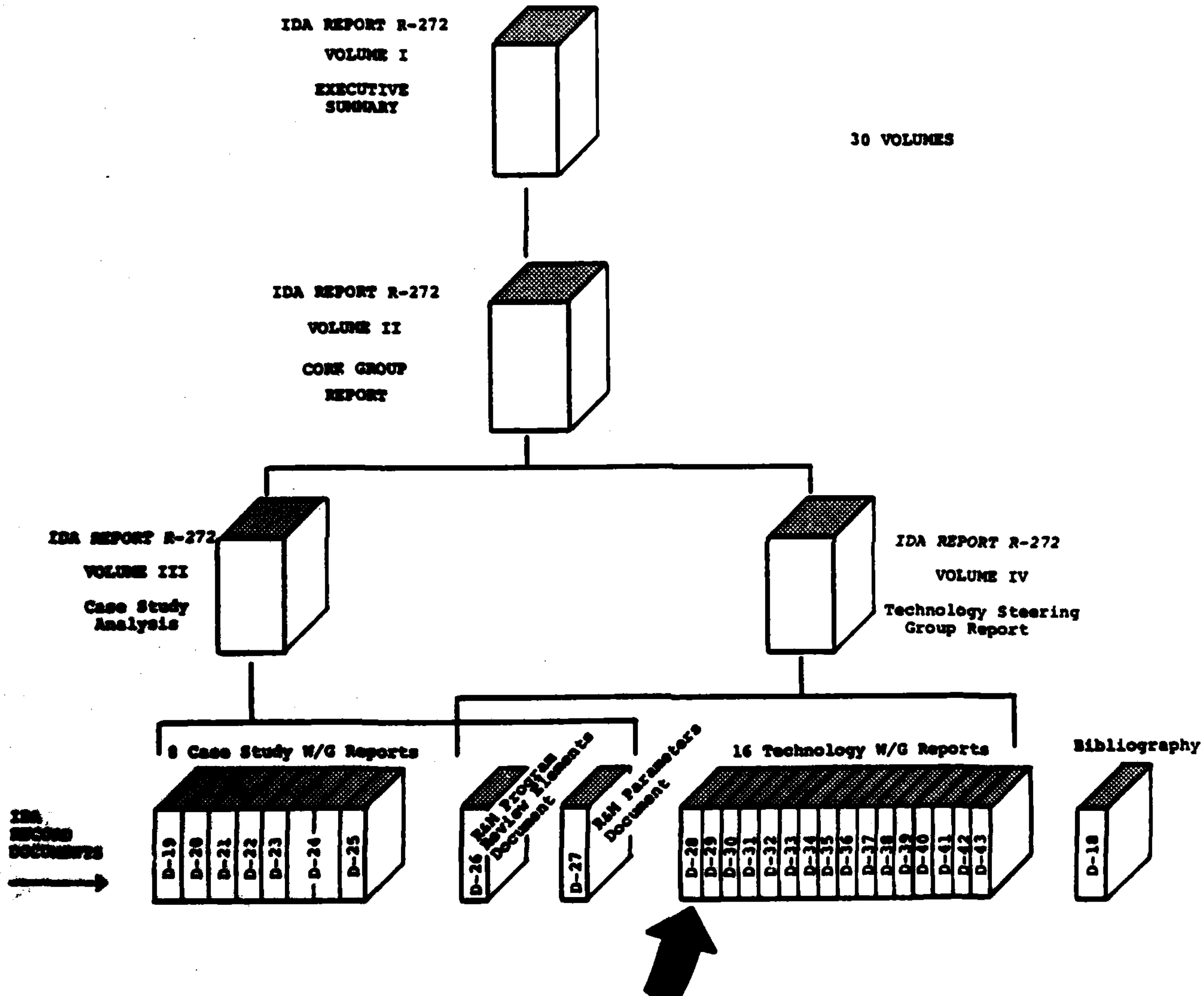

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PREFACE

As a result of the 1981 Defense Science Board Summer Study on Operational Readiness, Task Order T-2-126 was generated to look at potential steps toward improving the Material Readiness Posture of DoD (Short Title: R&M Study). This task order was structured to address the improvement of R&M and readiness through innovative program structuring and applications of new and advancing technology. Volume I summarizes the total study activity. Volume II integrates analysis relative to Volume III, program structuring aspects, and Volume IV, new and advancing technology aspects.

The objective of this study as defined by the task order is:

> "Identify and provide support for high payoff actions which the DoD can take to improve the military system design, development and support process so as to provide quantum improvement in R&M and readiness through innovative uses of advancing technology and program structure."

The scope of this study as defined by the task order is:

> To (1) identify high-payoff areas where the DoD could improve current system design, development program structure and system support policies, with the objective of enhancing peacetime availability of major weapons systems and the potential to make a rapid transition to high wartime activity rates, to sustain such rates and to do so with the most economical use of scarce resources possible, (2) assess the impact of advancing technology on the recommended approaches and guidelines, and (3) evaluate the potential and recommend strategies that might result in quantum increases in R&M or readiness through innovative uses of advancing technology.

The approach taken for the study was focused on producing meaningful implementable recommendations substantiated by quantitative data with implementation plans and vehicles to be provided where practical. To accomplish this, emphasis was placed upon the elucidation and integration of the expert knowledge and experience of engineers, developers, managers, testers and users involved with the complete acquisition cycle of weapons systems programs as well as upon supporting analysis. A search was conducted through major industrial companies, a director was selected and the following general plan was adopted.

General Study Plan

Vol. III	•	Select, analyze and review existing successful program
Vol. IV	•	Analyze and review related new and advanced technology
Vol. II	(•	Analyze and integrate review results
	(•	Develop, coordinate and refine new concepts
Vol. I	•	Present new concepts to DoD with implementation plan and recommendations for application.

The approach to implementing the plan was based on an executive council core group for organization, analysis, integration and continuity; making extensive use of working groups, heavy military and industry involvement and participation, and coordination and refinement through joint industry/service analysis and review. Overall study organization is shown in Fig. P-1.

The basic technology study approach was to build a foundation for analysis and to analyze areas of technology to surface: technology available today which might be applied more broadly; technology which requires demonstration to finalize and reduce risk; and technology which requires action today to provide reliable and maintainable systems in the future. Program structuring implications were also considered. Tools used to accomplish

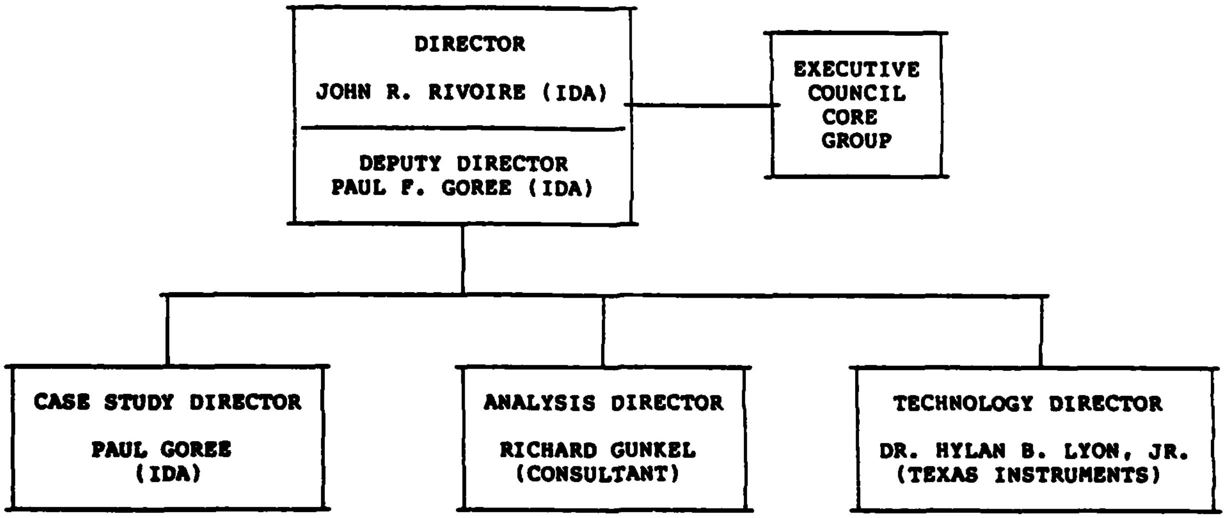

FIGURE P-1. Study Organization

this were existing documents, reports and study efforts such as the Militarily Critical Technologies List. To accomplish the technology studies, sixteen working groups were formed and the organization shown in Fig. P-2 was established.

This document records the activities and findings of the Technology Working Group for the specific technology as indicated in Fig. P-2. The views expressed within this document are those of the working group only. Publication of this document does not indicate endorsement by IDA, its staff, or its sponsoring agencies.

Without the detailed efforts, energies, patience and candidness of those intimately involved in the technologies studied, this technology study effort would not have been possible within the time and resources available.

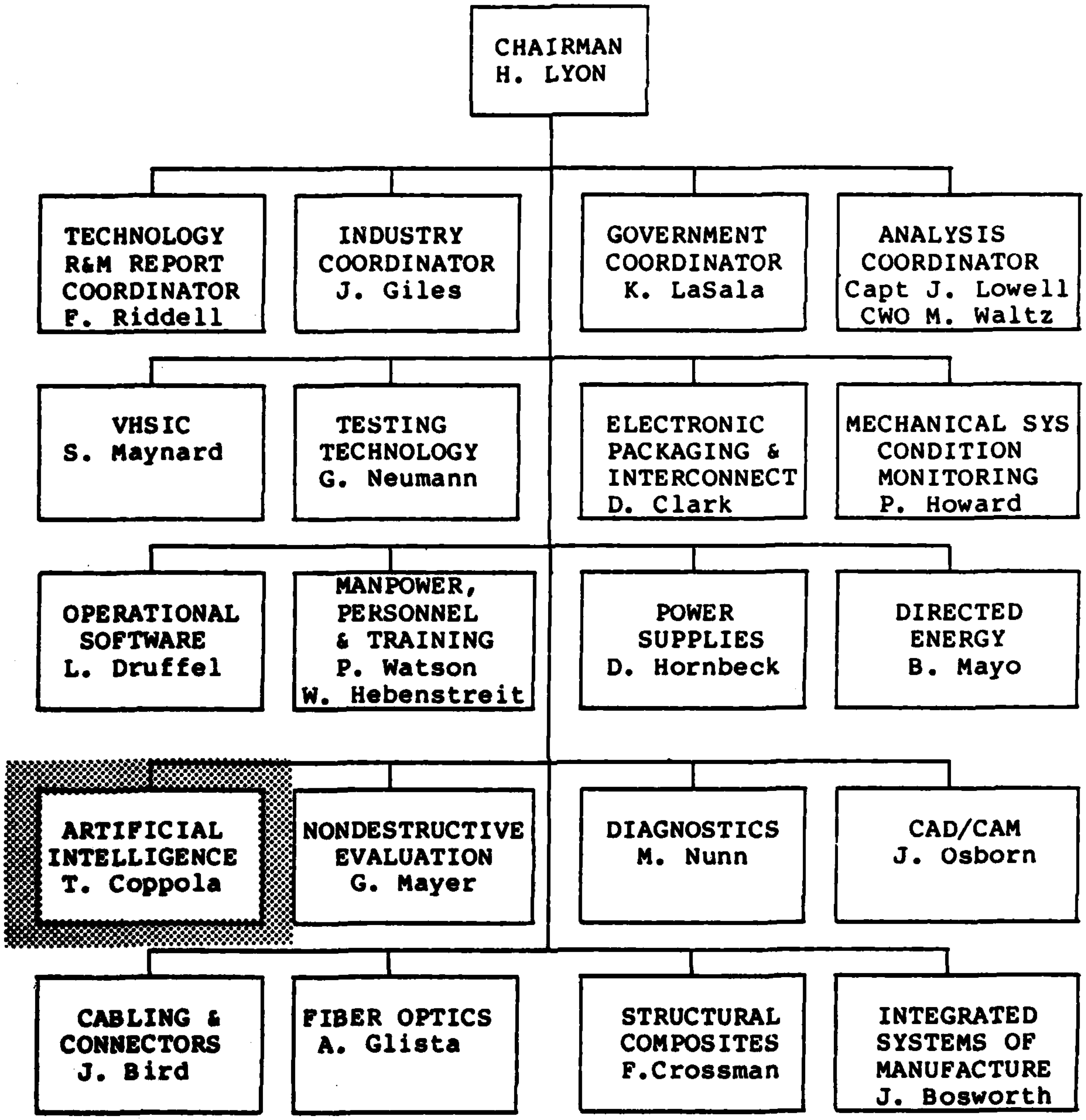

FIGURE P-2. Technology Study Organization

ARTIFICIAL INTELLIGENCE APPLICATIONS TO MAINTENANCE

JUNE 13, 1983

A REPORT FOR THE OSD/IDA R/M STUDY

ANTHONY COPPOLA
COMMITTEE CHAIRMAN

EXECUTIVE SUMMARY

THE MAINTENANCE OF MODERN MILITARY SYSTEMS EMPLOYS A VARIETY OF AUTOMATION. BUILT-IN-TEST (BIT) PROVIDES ON-LINE FAULT DETECTION AND SOME ISOLATION, AUTOMATIC TEST EQUIPMENT (ATE) IS INDISPENSABLE AT INTERMEDIATE AND DEPOT REPAIR STATIONS, AND AUTOMATED MAINTENANCE AIDS AND TRAINERS ABOUND.

THESE DEVELOPMENTS WERE DESIGNED TO SPEED MAINTENANCE AND TO COMPENSATE FOR DECLINING SKILL LEVELS IN THE MAINTENANCE FORCE. THEY ARE CURRENTLY FAR FROM SATISFACTORY. MODERN MAINTENANCE IS CHARACTERIZED BY EXCESSIVE FALSE ALARMS AND UNNECESSARY REMOVALS AT ALL LEVELS OF MAINTENANCE.

THE RESULTS OF THESE DEFICIENCIES ARE LONG MAINTENANCE TIMES, RESOURCES WASTED IN UNNECESSARY OR INEFFICIENT MAINTENANCE ACTIONS, AND SYSTEMS OUT OF ACTION WHICH NEED NOT BE. CORRECTING THESE PROBLEMS WOULD THEREFOR PROVIDE BOTH AN ECONOMIC ADVANTAGE AND A FORCE MULTIPLIER.

TO CREATE QUANTUM IMPROVEMENTS IN MAINTENANCE WILL REQUIRE THE APPLICATION OF RADICAL CHANGES TO THE TECHNOLOGY. ONE POSSIBILITY IS THE APPLICATION OF ARTIFICIAL INTELLIGENCE (AI) TECHNIQUES TO MAINTENANCE. AI IS BEGINNING TO SEE APPLICATION TO PRACTICAL PROBLEMS IN MANY DISCIPLINES, AND HENCE IS POTENTIALLY CAPABLE OF RELATIVELY RAPID IMPLEMENTATION INTO MILITARY SYSTEMS.

AT PRESENT, DOD EFFORTS IN APPLYING AI TO MAINTENANCE ARE SMALL AND EXPLORATORY.

THE TASK OF THE ARTIFICIAL INTELLIGENCE APPLICATIONS COMMITTEE WAS TO EXAMINE THE OPPORTUNITIES FOR APPLYING AI TO MAINTENANCE, ASSESS THE COSTS, RISKS, AND DEVELOPMENT TIMES REQUIRED, AND PROVIDE RECOMMENDATIONS TO THE DOD FOR ACTION.

THE COMMITTEE'S RECOMMENDATIONS ARE DETAILED IN SECTION 9 OF THIS REPORT, AND IN THE ATTACHED POSITION PAPERS. A SUMMARY FOLLOWS:

1. THE DOD SHOULD TAKE ADVANTAGE OF THE RELATIVE MATURITY OF THE TECHNOLOGY FOR CREATING EXPERT SYSTEMS. SPECIFIC APPLICATIONS OF MAINTENANCE EXPERT SYSTEMS SHOULD BE STARTED IMMEDIATELY, AND MULTI-APPLICATION MAINTENANCE EXPERTS DEVELOPED AND STANDARDIZED.

DEVELOP MAINTENANCE EXPERT SYSTEMS IMMEDIATELY FOR CURRENT MAINTENANCE APPLICATIONS WHERE THE EXISTING ATE HAS BEEN INADEQUATE. PERMIT THESE SYSTEMS TO BE BUILT IN ANY CONVENIENT LANGUAGE AND ARCHITECTURE, EXCEPT THAT TEST PROGRAMS GENERATED FOR OUTSIDE USE WOULD BE IN ATLAS.

DEVELOP VERSATILE MAINTENANCE EXPERTS FOR SPECIFIC DOMAINS (EG DIGITAL ELECTRONICS) CAPABLE OF USE IN DIFFERENT SYSTEMS. SYSTEM SPECIFIC DATA WOULD BE REQUIRED FOR EACH APPLICATION, BUT THE KNOWLEDGE BASE WOULD REMAIN THE SAME.

DEVELOP A TOOL TO AUTOMATE THE CREATION OF THE SYSTEM SPECIFIC DATA REQUIRED BY THE MAINTENANCE EXPERTS DESCRIBED IN THE PRECEDING PARAGRAPH.

2. DEVELOP "SMART" BUILT-IN-TEST (BIT) SYSTEMS TO REDUCE FALSE ALARMS, IDENTIFY INTERMITTENT FAILURES, IMPROVE BIT COVERAGE.

3. FUND APPLIED RESEARCH IN AI FOR MAINTENANCE TO IMPROVE EXPERT SYSTEM DESIGNS AND TO DEVELOP OTHER PROMISING APPLICATIONS. TOPICS COULD INCLUDE AUTOMATING CREATION OF MAINTENANCE MANUALS, APPLICATIONS TO MAINTENANCE INFORMATION SYSTEMS, AI BASED AUTOMATIC TEST PATTERN GENERATION (ATPG), VHSIC DESIGN FOR TESTABILITY, KNOWLEDGE BASED COMPUTER AIDED INSTRUCTION (CAI), AND SELF-IMPROVING DIAGNOSTICS.

4. FOSTER AN INTEGRATED DOD-INDUSTRY APPROACH. COORDINATE DOD ACTIVITY THROUGH A TRI-SERVICE WORKING GROUP UNDER THE EXISTING JLC PANEL ON AUTOMATIC TESTING. ENCOURAGE PRIVATE AVENUES OF DEVELOPMENT; CONTINUE TO SUPPORT INDUSTRY IR/D IN THE AREA.

TABLE OF CONTENTS

1.0. INTRODUCTION

THE MAINTENANCE OF MODERN MILITARY SYSTEMS EMPLOYS A VARIETY OF AUTOMATION. BUILT-IN-TEST (BIT) PROVIDES ON-LINE FAULT DETECTION AND SOME ISOLATION. AUTOMATIC TEST EQUIPMENT (ATE) IS INDISPENSABLE AT INTERMEDIATE AND DEPOT REPAIR STATIONS, AND AUTOMATED MAINTENANCE AIDS AND TRAINERS ABOUND.

THESE DEVELOPMENTS WERE DESIGNED TO SPEED MAINTENANCE AND TO COMPENSATE FOR DECLINING SKILL LEVELS IN THE MAINTENANCE FORCE. THEY ARE CURRENTLY FAR FROM SATISFACTORY. MODERN MAINTENANCE IS CHARACTERIZED BY EXCESSIVE FALSE ALARMS AND UNNECESSARY REMOVALS AT ALL LEVELS OF MAINTENANCE. EVEN WITH SUCCESSFUL USE OF ATE, THROUGHPUT IS FAR FROM IDEAL. ATE TOO OFTEN FAILS TO ISOLATE A FAILURE, REQUIRING SKILLFUL HUMAN INTERVENTION, OR EXPENSIVE "SHOTGUN" MAINTENANCE APPROACHES.

THE RESULTS OF THESE DEFICIENCIES ARE LONG MAINTENANCE TIMES, RESOURCES WASTED IN UNNECESSARY OR INEFFICIENT MAINTENANCE ACTIONS, AND SYSTEMS OUT OF ACTION WHICH NEED NOT BE. CORRECTING THESE PROBLEMS WOULD THEREFOR PROVIDE BOTH AN ECONOMIC ADVANTAGE AND A FORCE MULTIPLIER.

IT CAN BE EXPECTED THAT NORMAL EVOLUTION OF TESTING TECHNOLOGY WILL REDUCE THE SEVERITY OF THESE PROBLEMS. HOWEVER, QUANTUM IMPROVEMENTS WILL REQUIRE RADICAL CHANGES IN APPROACHES. ONE POSSIBILITY IS THE APPLICATION OF ARTIFICIAL INTELLIGENCE (AI) TECHNIQUES TO MAINTENANCE. AI IS BEGINNING TO SEE APPLICATION TO PRACTICAL PROBLEMS IN MANY DISCIPLINES, AND HENCE IS POTENTIALLY CAPABLE OF RELATIVELY RAPID IMPLEMENTATION INTO MILITARY SYSTEMS.

THE TASK OF THE ARTIFICIAL INTELLIGENCE APPLICATIONS COMMITTEE WAS TO EXAMINE THE OPPORTUNITIES FOR APPLYING AI TO MAINTENANCE, ASSESS THE COSTS, RISKS, AND DEVELOPMENT TIMES REQUIRED, AND PROVIDE RECOMMENDATIONS TO THE DOD FOR ACTION. THIS REPORT PRESENTS THEIR FINDINGS AND RECOMMENDATIONS.

2.0. COMMITTEE APPROACH AND MEMBERSHIP

FROM A VARIETY OF SOURCES, 28 PEOPLE WERE IDENTIFIED AS POTENTIAL CONTRIBUTORS TO THE STUDY. EACH OF THESE WERE INFORMED OF THE STUDY OBJECTIVES AND INVITED TO CONTRIBUTE POSITION PAPERS DESCRIBING THEIR RECOMMENDATIONS TO DOD WITH THEIR BEST ESTIMATES OF COSTS, BENEFITS, AND TECHNOLOGICAL RISKS. ALL RESPONSES WERE CONSOLIDATED BY THE COMMITTEE CHAIRMAN INTO THIS REPORT. CONSIDERED AS A POSITION PAPER WAS A COPY OF PROPOSALS SUBMITTED BY THE AIR FORCE HUMAN RESOURCES LABORATORY TO A TRI-SERVICE WORKING GROUP. OTHER INPUTS WERE A SURVEY BY THE ROME AIR DEVELOPMENT CENTER ON ARTIFICIAL INTELLIGENCE APPLICATIONS TO TESTABILITY AND VARIOUS ARTICLES IN THE LITERATURE. THE CHAIRMANS CONSOLIDATION WAS AIDED GREATLY BY THE TECHNICAL ADVICE OF MR. ROBERT SCHRAG, WHO REVIEWED EACH ITERATION OF THE DRAFT.

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3.0. ORGANIZATION OF THIS REPORT

THE NEXT SECTION OF THIS REPORT WILL ILLUSTRATE SOME OF THE PROBLEMS WITH CURRENT MAINTENANCE OF MILITARY EQUIPMENT. FOLLOWING IT WILL BE AN INTRODUCTION TO ARTIFICIAL INTELLIGENCE. THE NEXT SECTION WILL DISCUSS THE EXTENT OF CURRENT APPLICATIONS OF AI TO MAINTENANCE, AND THE ULTIMATE, THOUGH PERHAPS NOT REALIZABLE, IMPLICATIONS OF AI TECHNOLOGY TO MAINTENANCE. FOLLOWING THIS WILL BE A DISCUSSION OF CAVEATS AND POTENTIAL TRAPS IN APPLYING AI. AFTER A BRIEF DISCUSSION OF PRESENT AI RESEARCH IN MAINTENANCE APPLICATIONS, THE FINAL SECTION WILL PRESENT A CONSOLIDATION OF THE COMMITTEES RECOMMENDATIONS TO DOD. INDIVIDUAL POSITION PAPERS BY THE COMMITTEE MEMBERS ARE ATTACHED AT THE END OF THE REPORT.

ILLUSTRATION OF MAINTENANCE PROBLEMS E-3A RADAR TESTS

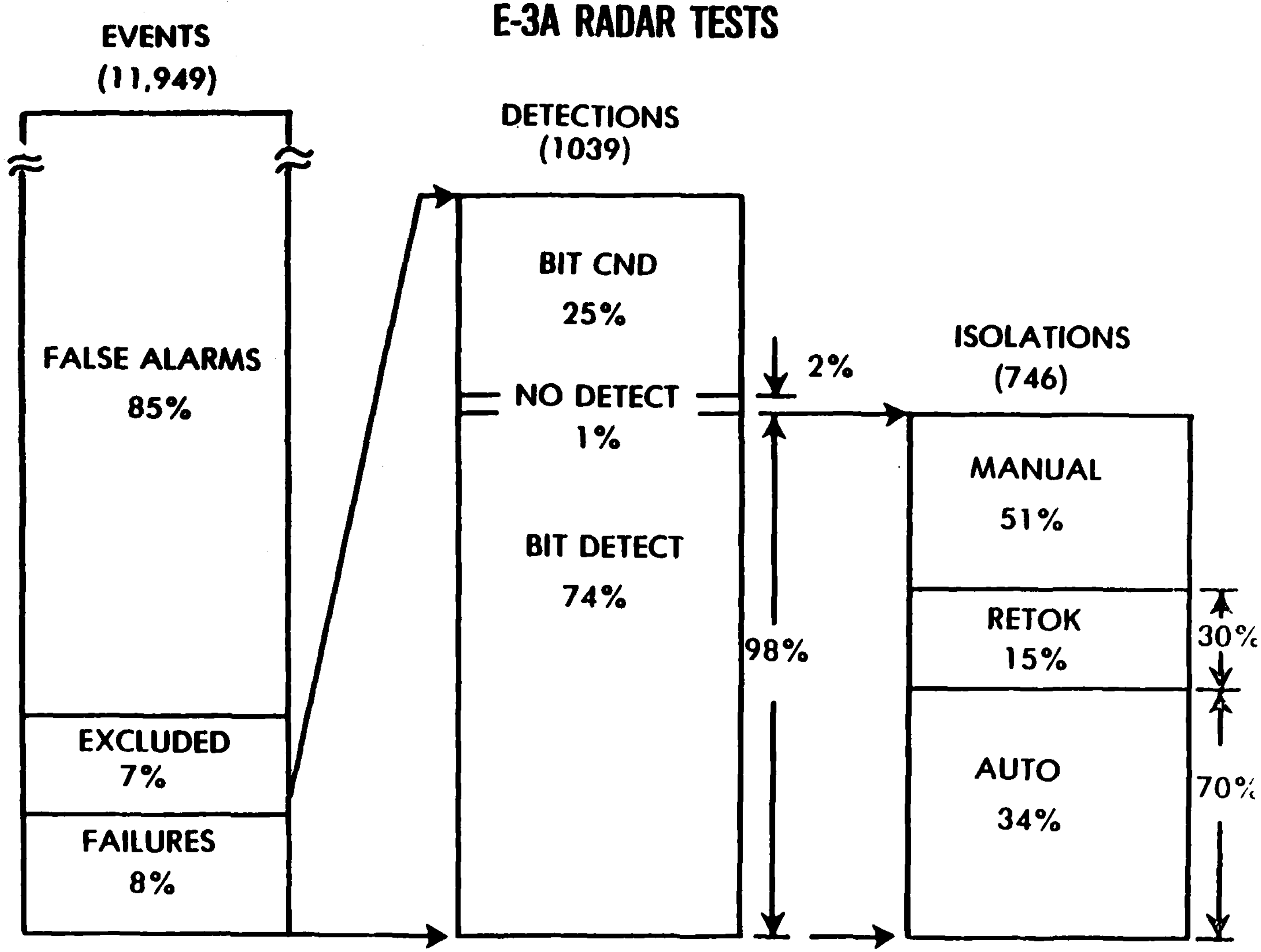

FIGURE 1

4.0. ILLUSTRATIONS OF MAINTENANCE PROBLEMS

FIGURE 1 SHOWS A SUMMARY OF INFORMATION COMPILED BY THE AIR FORCE TEST AND EVALUATION CENTER DURING TESTS OF THE E-3A (AWACS) RADAR. OF THE NEARLY 12,000 INDICATIONS OF MALFUNCTION, SEVEN PERCENT WERE EXCLUDED AS NOT RELEVANT TO THE TEST PROGRAM (FAILURES CAUSED BY EXTERNAL CAUSES, ETC.) OF THE REMAINDER, FALSE ALARMS OUTNUMBERED FAILURES (ITEMS ON WHICH MAINTENANCE WAS PERFORMED) BY MORE THAN TEN TO ONE. ALTHOUGH THESE WERE RECOGNIZED AS FALSE ALARMS BEFORE STARTING THROUGH THE MAINTENANCE CHAIN, THEY REPRESENT AT THE LEAST A SOURCE OF ANNOYANCE TO A BUSY AIRCREW. OF THOSE EIGHT PERCENT CONSIDERED AS VALID INDICATIONS OF FAILURE, 25% COULD NOT BE DUPLICATED AT THE FIRST MAINTENANCE CHECK (CND). THESE MIGHT BE ADDITIONAL FALSE ALARMS OR, PERHAPS, INTERMITTENT FAILURES WHICH OCCUR ONLY UNDER THE FLIGHT ENVIRONMENT. IN EITHER EVENT, 25% OF THE FIRST MAINTENANCE ACTIONS ACCOMPLISHED NOTHING.

OF THE REMAINING MAINTENANCE ACTIONS, 98% OF THE FAILURES WERE DETECTED BY THE BIT, LEAVING TWO PERCENT TO BE FOUND BY MANUAL MEANS. THIS IS A CREDITABLE PERFORMANCE, BUT UNFORTUNATELY NOT TRUE OF ALL SYSTEMS.

WHEN THE ATTEMPT WAS MADE TO ISOLATE THE FAILURES DETECTED BY BIT, IT WAS FOUND THAT THE AUTOMATIC TEST EQUIPMENT COULD NOT IDENTIFY THE FAILED COMPONENT IN HALF OF THE CASES, WHICH BY NECESSITY REVERTED TO MANUAL PROCEDURES. ALSO NOTEWORTHY IS THAT 15% OF THE CASES RETESTED AS APPARENTLY GOOD (RETOK), REQUIRING NO MAINTENANCE.

THE MESSAGE OF THESE FIGURES IS THAT THERE IS TOO MUCH UNNECESSARY MAINTENANCE, THAT THE AUTOMATED TECHNIQUES ARE CONTRIBUTING TO UNNECESSARY MAINTENANCE, THAT THEY ARE NOT SUFFICIENTLY REDUCING MANUAL TROUBLESHOOTING, AND, PERHAPS, THAT SOME FAILURES ARE ESCAPING THE MAINTENANCE PROCEDURES.

THE FALSE ALARM PROBLEMS OF AWACS ARE BY NO MEANS UNIQUE. AN ON-BOARD FAILURE RECORDER FOR THE F-111D PROVED INEFFECTUAL BECAUSE A SIMILAR RATIO OF FAILURE INDICATIONS TO ACTUAL FAILURES. FALSE ALARMS IN THE F-16 CAUSED INNOVATIONS IN BIT MECHANIZATION WHICH WILL BE DISCUSSED LATER. OUTSIDE THE MILITARY, A STUDY BY LOCKHEED FOR THE ELECTRIC POWER RESEARCH INSTITUTE (1977) FOUND THE SAME PROBLEM IN NUCLEAR POWER PLANT CONTROL ROOMS. ONE RATHER FRIGHTENING PICTURE IN THEIR REPORT SHOWS A CONTROL ROOM IN WHICH 65 WARNING LIGHTS COULD BE SEEN. ALL WERE IGNORED BY THE OPERATORS AS FALSE ALARMS.

ANOTHER UNIVERSAL MAINTENANCE PROBLEM IS THE NUMBER OF ITEMS WHICH TEST GOOD IN MAINTENANCE. FIGURES GATHERED FROM THE UNITED STATES AIR FORCE, THE CANADIAN AIR FORCE, THE NAVY AVIONICS REPAIR FACILITIES AND THE COMMERCIAL AIRLINES ALL SHOW THAT 30% OR MORE OF UNITS IN MAINTENANCE TEST GOOD. HENCE, A SIGNIFICANT AMOUNT OF MAINTENANCE IS EITHER UNNECESSARY OR INEFFECTUAL.

IN MARCH 1983, THE WARNER-ROBINS AIR LOGISTICS CENTER PROVIDED THE FOLLOWING LIST OF MAINTENANCE PROBLEMS:

- O TEST PROGRAMS PROCEED IN SEQUENCE UNTILL A FAILURE IS FOUND. SOME OF THESE RUN AS LONG AS THREE AND ONE-HALF HOURS. IN ONE OF THESE, THE MOST COMMON FAILURE WAS DETECTED IN THE LAST SEGMENTS OF THE PROGRAM.

- O MEMORY DEVICES ARE PARTICULARLY DIFFICULT TO TEST.

- O THE ATE DOES NOT ISOLATE ALL THE FAILURES, LEAVING THOSE NOT FOUND TO THE INGENUITY OF THE MAINTENANCE PERSONNEL.

- O THE FAULT ISOLATION IS TOO OFTEN AMBIGUOUS. FOR EXAMPLE, WHILE THE F-15 ATE NORMALLY ISOLATES A FAILURE TO A SINGLE PART, IT CAN ALSO RETURN A LIST OF SUSPECT PARTS AS HIGH AS 15. MEMORY DEVICES ARE ESPECIALLY PRONE TO HIGH AMBIGUITY IN ISOLATION.

- O THE TEST PROGRAM MAY ISOLATE TO A STRING OF COMPONENTS, WHICH WOULD ALL BE REPLACED OR FURTHER ISOLATION PERFORMED BY MANUAL MEANS. SOME HYBRID CIRCUITS COST FROM $300 TO $3,000 MAKING "SHOTGUN" REPLACEMENT AN EXPENSIVE PROPOSITION. EVEN A STRING OF RELATIVELY CHEAP PARTS REPRESENTS A SIGNIFICANT MAINTENANCE COST IN MANHOURS IF ALL ARE REPLACED.

- O THE ATE WILL NOT ISOLATE CHASSIS PROBLEMS (EG BROKEN WIRES)

THESE PROBLEMS TRANSLATE INTO OVERLOADED MAINTENANCE FACILITIES, INCREASED REQUIREMENTS FOR SPARE UNITS IN THE PIPELINE, AND EXCESSIVE COSTS FOR LABOR AND CONSUMABLES.

IN SUMMARY, THERE IS AMPLE OPPORTUNITY FOR INCREASING READINESS SIGNIFICANTLY BY ALLEVIATING THESE MAINTENANCE DEFICIENCIES. SIGNIFICANT IMPROVEMENTS IN NEW SYSTEMS MAY BE POSSIBLE BY MERELY DESIGNING THE HARDWARE TO BE EASIER TO TEST. ANOTHER APPROACH, APPLICABLE TO BOTH NEW AND EXISTING SYSTEMS IS TO MAKE THE TEST EQUIPMENT "SMARTER". SIGNIFICANT IMPROVEMENTS WILL REQUIRE SIGNIFICANT CHANGES IN TECHNOLOGY, INCORPORATING THE TECHNIQUES OF ARTIFICIAL INTELLIGENCE.

5.0. INTRODUCTION TO ARTIFICIAL INTELLIGENCE

THERE IS NO STANDARD DEFINITION OF ARTIFICIAL INTELLIGENCE. AN OFTEN USED DEFINITION IS THE CAPABILITY OF A MACHINE TO DO A TASK WHICH IF DONE BY A HUMAN WOULD BE CONSIDERED TO REQUIRE INTELLIGENCE. THUS AN AUTOMOBILE WOULD NOT BE AN EXAMPLE OF AI, SINCE WALKING IS NOT CONSIDERED TO REQUIRE INTELLIGENCE. A CHESS PLAYING COMPUTER, ON THE OTHER HAND, IS AN EXAMPLE OF AI.

THIS DEFINITION IS, HOWEVER, TOO SIMPLISTIC. UNDER IT, ALL BIT AND ATE WOULD BE CONSIDERED MANIFESTATIONS OF AI, SINCE LOCATING FAULTS REQUIRES INTELLIGENCE. HOWEVER, THE BRUTE FORCE APPROACH OF A FIXED SEQUENCE OF STIMULUS-RESPONSE COMPARISONS TO PREESTABLISHED CRITERIA CANNOT BE CONSIDERED AN IMPRESSIVE SHOW OF INTELLIGENCE IN MACHINE OR MAN. HENCE, A MORE SOPHISTICATED DEFINITION IS CALLED FOR.

TO ELIMINATE THE TRIVIAL MECHANIZATIONS FALLING UNDER THE SIMPLE DEFINITION, WE SHALL ADD THE CRITERIA THAT THE MACHINE MUST HAVE THE CAPABILITY OF FORMING AND MANIPULATING ABSTRACTIONS. THIS WOULD INCLUDE SUCH ACTIVITIES AS FORMING HYPOTHESES (EG THE LOCATION OF A FAILURE), THE TESTING OF HYPOTHESES, LEARNING, AND INFERENCE.

IT SHOULD BE NOTED THAT, FOR OUR PURPOSES, IT DOES NOT MATTER WHETHER OR NOT THE MACHINE SOLVES A PROBLEM IN THE SAME MANNER A HUMAN WOULD. WHILE MUCH RESEARCH IN AI IS DIRECTED AT UNDERSTANDING HUMAN INTELLIGENCE, WE WILL BE COMPLETELY INDIFFERENT TO THE PROCESSES INVOLVED, SO LONG AS THEY REPRESENT THE MOST COST-EFFECTIVE SOLUTIONS TO THE PRACTICAL APPLICATIONS OF INTEREST.

5.1. AI FIELDS OF STUDY

THERE IS ALSO NO STANDARD BREAKDOWN OF AI FIELDS OF STUDY. FOR CONVENIENCE WE SHALL USE A LIST OF TOPICS EXTRACTED FROM "PRINCIPLES OF ARTIFICIAL INTELLIGENCE" BY NILS J. NILSSON (1980,TIOGA PUBLISHING CO., PALO ALTO, CA.). IN THIS SECTION WE WILL BRIEFLY DESCRIBE THE OBJECTIVES OF EACH TOPIC. IN THE NEXT SECTION, THEIR CURRENT AND POTENTIAL APPLICATIONS TO MAINTENANCE WILL BE DISCUSSED. THE FIELDS OF STUDY ARE:

5.1.1. NATURAL LANGUAGE PROCESSING.

FOR OUR PURPOSES, THIS FIELD OF STUDY INCLUDES ALL ATTEMPTS TO MAKE A MACHINE CAPABLE OF UNDERSTANDING INPUTS IN NATURAL LANGUAGE (IE ENGLISH) WHETHER TYPED OR SPOKEN. WE SHALL ALSO INCLUDE THE SYNTHESIS OF MACHINE REPLIES IN WRITTEN OR SPOKEN ENGLISH.

IT HAS BEEN EXTREMELY DIFFICULT TO GIVE A MACHINE THE CAPABILITY OF "UNDERSTANDING" EVEN SUBSETS OF NATURAL LANGUAGE. THIS IS BECAUSE A MESSAGE IS UNDERSTOOD NOT ONLY BY ITS TEXT, BUT BY THE TOTAL EXPERIENCE OF ITS RECEIVER. FOR EXAMPLE, CONSIDER THE FOLLOWING CONVERSATION:

"HUNGRY?"

"I'VE GOT A MACDONALDS COUPON."

"KEYS?"

"HERE. LET'S GO."

THE MANY NON-SPOKEN PORTIONS OF THE CONVERSATION ARE READILY UNDERSTOOD BY A HUMAN, AND THE MESSAGE MAKES SENSE. TO A MACHINE, IT IS A SEQUENCE OF NON-SEQUITORS.

THIS IS NOT TO SAY THAT USEFUL LANGUAGE RECOGNITION HAS NOT BEEN ACCOMPLISHED. A SIMULATED ROBOT MANIPULATOR CALLED SHRDLU CAN CARRY ON MEANINGFUL DIALOGS IN THE LIMITED SCOPE OF ITS WORLD OF BLOCKS ON A TABLE TOP. KNOBS, AN EXPERT SYSTEM IN DEVELOPMENT FOR TACTICAL AIR MISSION PLANNING, HAS AN EXTENSIVE NATURAL LANGUAGE UNDERSTANDING CAPABILITY.

RECOGNIZING SPOKEN SPEECH COMPOUNDS THE PROBLEMS OF UNDERSTANDING THE MEANING OF THE MESSAGE WITH PROBLEMS OF RECOGNIZING THE MESSAGE ITSELF. SEPARATING WORDS IN SPOKEN SENTENCES HAS PROVEN A DIFFICULT CHORE. PRACTICAL USE IS BEING MADE OF SPOKEN CUES TO MACHINES WHERE A CUE IS A ONE WORD DIRECTION SUCH AS "BACK","NEXT",OR "TWO". EVEN HERE, THE MACHINE MUST BE TRAINED TO THE VOICE OF ITS OPERATOR AND MAY NOT RESPOND TO ANOTHER SPEAKER.

SYNTHESISING SPEECH IS MUCH EASIER THAN UNDERSTANDING IT AS THE PLETHORA OF TALKING COMPUTERS INDICATES. THE MAIN PROBLEMS IN SPEECH SYNTHESIS IS GIVING THE COMPUTER THE ABILITY TO KNOW WHAT TO SAY.

5.1.2. INFERENTIAL RETRIEVAL FROM DATA BASES.

THE DESIGN OF EFFICIENT DATA BASES IS A COMPUTER SCIENCE FIELD OF INTEREST. IT BECOMES AN AI CONSIDERATION WHEN THE DESIRED RETRIEVAL IS A DEDUCTION RATHER THAN A STORED FACT. FOR EXAMPLE, AN AI MACHINE WITH INTELLIGENT RETRIEVAL COULD SOLVE THE LOGIC PUZZLES WHICH PROVIDE SUCH FACTS AS "JOHN AND THE ENGINEER WENT TO BERMUDA" AND "MARIE TRAVELLED BY BUS." WITH THE READER REQUIRED TO DEDUCE THE OCCUPATION AND VACATION CHOICE OF ALL THE NAMES PROVIDED. LIKE LANGUAGE UNDERSTANDING, THIS REQUIRES A STORE OF "COMMON KNOWLEDGE" PERTINENT TO THE PROBLEMS OF INTEREST (EG BERMUDA IS NOT ACCESSIBLE BY BUS) AS WELL AS INFERENTIAL MECHANISMS. A PRACTICAL SYSTEM WILL ALSO HAVE TO UNDERSTAND QUERIES, MAKING NATURAL LANGUAGE UNDERSTANDING ABILITY A VALUABLE ADJUNCT FEATURE.

5.1.3. THEOREM PROVING.

THERE ARE SEVERAL PROGRAMS WHICH WILL AUTOMATICALLY PROVE MATHEMATICAL THEOREMS. THE TECHNIQUES DEVELOPED FOR THESE ARE OF SIGNIFICANT VALUE TO OTHER AI APPLICATIONS. THEOREM PROVING METHODS CAN BE EXTENDED TO INFORMATION RETRIEVAL AND FAILURE LOCATION WHEN THESE TASKS ARE FORMALIZED AS THEOREMS TO BE PROVEN. (EG A THEOREM TO BE PROVEN COULD BE THAT A FAILURE IS LOCATED IN A GIVEN COMPONENT.) THEOREM-PROVING TECHNIQUES ATTEMPT TO ESTABLISH A PROCEDURE FOR SELECTING FROM AMONG POSSIBLE RULES TO APPLY TO THE PROBLEM AND TO

ESTABLISH SUBPROBLEMS LEADING TO THE SOLUTION.

5.1.4. AUTOMATIC PROGRAMMING.

STRICTLY SPEAKING, EXISTING COMPILERS ARE AUTOMATIC PROGRAMMERS. THEY ACCEPT THE HIGHER ORDER LANGUAGE AND WRITE AN OBJECT CODE TO DO A SPECIFIED JOB. IN THE AI SPHERE, THE INTEREST IS IN MACHINES WHICH WILL CONVERT HIGH LEVEL DESCRIPTIONS, THE ULTIMATE BEING AN ENGLISH INPUT, TO AN EXECUTABLE PROGRAM. THIS COULD INCLUDE DIALOGUE BETWEEN MACHINE AND USER TO RESOLVE AMBIGUITIES. AUTOMATIC PROGRAMMING SYSTEMS CAN ALSO PROVIDE THE VALUABLE ADDED BENEFIT OF VERIFYING THAT THE PROGRAM PRODUCED DOES THE INTENDED JOB. CONTRIBUTIONS OF WORK IN THE FIELD INCLUDE CONCEPTS OF "DEBUGGING" AS A STRATEGY. IT CAN BE EASIER TO MODIFY A QUICKLY GENERATED ERRONEOUS PROGRAM THAN TO PRODUCE A PERFECT PRODUCT ON THE FIRST PASS. ACHIEVING THE GOALS OF AUTOMATIC PROGRAMMING, WILL, HOWEVER, REQUIRE A LONG TERM EFFORT.

5.1.5. COMBINATORIAL/SCHEDULING PROBLEMS.

THE CLASSIC EXAMPLE OF THIS CLASS OF PROBLEM IS THE "TRAVELLING SALESMAN PROBLEM", IN WHICH THE SOLVER ATTEMPTS TO FIND A ROUTING WHICH WILL PERMIT A SALESMAN TO VISIT A GIVEN NUMBER OF CITIES WITH A MINIMUM DISTANCE TRAVELLED. SOLUTIONS TO THESE PROBLEMS GENERATE A "COMBINATORIAL EXPLOSION" OF POSSIBILITIES. THE MOST EFFICIENT SOLUTIONS KNOWN FOR THIS CLASS OF PROBLEM REQUIRE SOLUTION TIMES WHICH GROW EXPONENTIALLY WITH THE SIZE OF THE PROBLEM. AI EFFORTS HAVE BEEN DIRECTED TOWARDS DELAYING AND MODERATING THE COMBINATORIAL EXPLOSION, USING KNOWLEDGE ABOUT THE PROBLEM DOMAIN.

5.1.6. MACHINE PERCEPTION

UNDERSTANDING OF SPOKEN SPEECH IS AN EXAMPLE OF MACHINE PERCEPTION. WE HAVE CHOSEN TO INCLUDE THIS UNDER NATURAL LANGUAGE UNDERSTANDING. SIMILARLY, SIMULATION OF ANY OF THE HUMAN SENSES, AND USE OF SENSORY INPUTS SUCH AS INFRA-RED, RADAR RETURNS, ETC., CAN BE CONSIDERED MACHINE PERCEPTION. THE PROBLEMS CAN BE REPRESENTED BY A DISCUSSION OF THE INTERPRETATION OF VISUAL IMAGES.

DETECTORS OF LIGHT INTENSITY CAN BE CONSTRUCTED. AI PROGRAMS EXIST TO DEDUCE GEOMETRIC FEATURES SUCH AS STRAIGHT LINES AND TO SEPARATE THE BOUNDARIES OF VARIOUS SOLID OBJECTS. THE ULTIMATE GOAL IS TO PRODUCE A HIGH LEVEL DESCRIPTION, SUCH AS "A HOUSE WITH THREE WINDOWS". ACHIEVEMENT OF THIS GOAL IS YET TO COME, BUT HERE AGAIN KNOWLEDGE OF THE PROBLEM DOMAIN MAY BE THE KEY. (IT SHOULD BE EASIER TO DISTINGUISH A TANK FROM A TRUCK IN A CONVOY, FOR EXAMPLE, THAN TO IDENTIFY EVERY OBJECT IN A PHOTOGRAPH OF TIMES SQUARE.)

5.1.7. EXPERT CONSULTING SYSTEMS

THERE NOW EXIST A NUMBER OF AUTOMATED CONSULTANTS TO AID IN SOLVING VARIOUS PROBLEMS, INCLUDING FAULT DIAGNOSIS. ONE AI TECHNIQUE EMPLOYED IN SUCH SYSTEMS IS RULE BASED DEDUCTION. SPECIFIC DOMAIN KNOWLEDGE AND PROBLEM SOLVING RULES OBTAINED FROM A HUMAN EXPERT ARE USED BY THE MACHINE TO FORMULATE AND TEST HYPOTHESES. THE SYSTEM WILL CREATE A DIALOG WITH ITS USER TO OBTAIN DATA NEEDED BY ITS RULES, AND WILL USE INFERENTIAL PROCEDURES TO WORK WITH INCOMPLETE OR CONFLICTING DATA.

DIFFICULTIES IN CREATING EXPERT SYSTEMS ARISE IN THE REDUCTION OF THE EXPERTS' KNOWLEDGE TO A SET OF RULES. EVEN A WILLING EXPERT MAY BE UNABLE TO SO REDUCE HIS KNOWLEDGE. REPRESENTING THE KNOWLEDGE BASE IS ALSO A KEY PROBLEM.

OBVIOUSLY, MANY DEVELOPMENTS IN THE AI FIELDS DESCRIBED ABOVE WILL HAVE THEIR APPLICATIONS TO EXPERT SYSTEMS.

5.1.8. ROBOTICS

ROBOTS ARE THE AI APPLICATION MOST VISIBLE TO THE PUBLIC, AND THOUSANDS ARE IN PRACTICAL USE. HOWEVER, THE TYPICAL APPLICATION IS FAR LESS SOPHISTICATED THAN THE HIGHLY PUBLICIZED EXPIREMENTAL MODELS. A PRESENTATION ON GENERAL MOTORS ROBOTIC APPLICATIONS AT THE 1983 ANNUAL RELIABILITY AND MAINTAINABILITY SYMPOSIUM POINTED OUT THAT THE ROBOT IN A WORK STATION IS OFTEN VIRTUALLY HIDDEN BEHIND A COMPLEX OF AUTOMATIC POSITIONING MACHINERY NEEDED TO ASSURE THE PARTS MANIPULATED BY THE ROBOT ARE ALWAYS IN THE EXPECTED PLACE. DEVELOPMENTS IN ROBOTICS ARE AIMED AT CREATING PLANNING CAPABILITIES TO ELEVATE THE ROBOT FROM A MERE MANIPULATOR OF ITEMS IN A STRUCTURED SITUATION, AND AT COUPLING MACHINE PERCEPTION TO REDUCE ITS DEPENDENCE ON AN ORDERLY ENVIRONMENT.

6.0. CURRENT AND POTENTIAL APPLICATIONS OF AI TO MAINTENANCE

THIS SECTION WILL DISCUSS THE MAINTENANCE APPLICATIONS OF EACH OF THE AI TOPICS DESCRIBED ABOVE. EXISTING APPLICATIONS OF AI IN MAINTENANCE OR IN ANALOGOUS FIELDS WILL BE DESCRIBED. TECHNIQUES ON THE FRINGES OF AI OR USEFUL TO AI APPLICATIONS WILL BE ALSO BE COVERED. POTENTIAL NEAR TERM APPLICATIONS WILL BE IDENTIFIED. FINALLY, THE ULTIMATE IMPLICATIONS OF THE FIELD OF STUDY WILL BE POSTULATED. THESE ARE THE APPLICATIONS WHICH COULD BE MADE IF ALL THE GOALS OF THE AI FIELD WERE ACHIEVED. THEY ARE, OF COURSE, FAR OUT BOTH IN TIME AND IN IMAGINATION, AND MAY NEVER BECOME POSSIBLE. NEVERTHELESS, THEY REPRESENT A SET OF GOALS AGAINST WHICH PROGRESS CAN BE MEASURED.

6.1. NATURAL LANGUAGE PROCESSING.

AS MENTIONED ABOVE, SHRDLU CAN CARRY ON A CONVERSATION WITH ITS USER ABOUT ITS LIMITED DOMAIN. A MEDICAL DIAGNOSIS SYSTEM, MYCIN, CAN DO THE SAME WITH A DOCTOR ABOUT BACTERIAL INFECTIONS. HENCE, IT IS CERTAINLY A NEAR TERM POSSIBILITY THAT A MAINTENANCE SYSTEM CAN BE MADE TO CONVERSE WITH ITS USER IN A USEFUL SUBSET OF ENGLISH. THIS WOULD BE ACCOMPLISHED BY THE USER TYPING IN HIS SIDE OF THE CONVERSATION. THE MACHINE COULD RESPOND BY PRINTOUT, CRT DISPLAY OR SYNTHESISED SPEECH.

SPOKEN INTERACTION WOULD BE HIGHLY DESIRABLE AS IT WOULD FREE THE MAINTENANCE MAN FROM THE TERMINAL. HE COULD THEN HAVE BOTH HANDS FREE AND COULD OPERATE IN REMOTE LOCATIONS USING A PORTABLE HEADSET TO CONSULT HIS COMPUTER. AT THIS TIME THERE EXIST MAINTENANCE TRAINERS WHICH RESPOND TO VOICE CUES, WHICH IS CERTAINLY A STEP FORWARD. HOWEVER, VERBAL COMMUNICATION IN NEAR CONVERSATIONAL STYLE MUST BE CONSIDERED A FAR OUT APPLICATION.

6.2. INFERENTIAL RETRIEVAL FROM DATA BASES

CURRENT APPLICATIONS TO MAINTENANCE OF THIS TOPIC MUST BE CONSIDERED ONLY ON THE FRINGES OF AI, WITH THE POSSIBLE EXCEPTION OF AUTOMATIC TEST PATTERN GENERATION (ATPG). ATPG IS USED TO GENERATE THE TEST PATTERNS FOR DIGITAL LOGIC. AT PRESENT, THE MACHINE IS SUPERIOR TO THE HUMAN IN FORMULATING TESTS FOR COMBINATORIAL LOGIC, AND INFERIOR IN SEQUENTIAL LOGIC. NEAR TERM POSSIBILITIES ARE THE IMPROVEMENT OF MACHINE HANDLING OF SEQUENTIAL LOGIC AND DEVELOPMENT OF ATPG FOR ANALOG CIRCUITRY. THE ULTIMATE POTENTIAL WOULD BE THE COMPLETE ELIMINATION OF THE MANUAL PART OF THE PROCESS.

ON THE FRINGE OF AI IS THE USE OF COMPUTERIZED MODELS TO DIRECT THE TESTING PROCESS. THERE ARE THREE EXISTING PROGRAMS WHICH WILL USE A STORED REPRESENTATION OF AN EQUIPMENT TO REDUCE THE NUMBER OF TESTS NEEDED TO ISOLATE A FAILURE. THE FIRST OF THESE WAS LOGMOD (DETEX CORP.). THE LOGMOD DATA BASE IS A USER PREPARED LOGICAL MODEL OF THE SYSTEM. USING THIS MODEL, A HEURISTIC (RULE FOLLOWING) PROCEDURE USES THE RESULTS OF EACH TEST MADE BY THE MAINTENANCE MAN TO DIRECT HIM TO THE NEXT TEST SUCH THAT EACH TEST ELIMINATES HALF OF THE SUSPECT

COMPONENTS UNTIL THE FAILED UNIT IS ISOLATED. THE STAMP PROGRAM (ARINC) USES A NODAL REPRESENTATION OF THE SYSTEM AND PROVIDES VARIOUS SEARCH OPTIONS SUCH AS ELIMINATING COMPONENTS WITH HALF THE PREDICTED FAILURE RATE. THE THIRD SYSTEM, FIND, IN DEVELOPMENT BY HUGHES, HAS SIMILAR FEATURES.

THE MODULAR AUTOMATIC TEST EQUIPMENT (MATE) OFFICE OF THE AIR FORCE AERONAUTICAL SYSTEMS DIVISION HAS CREATED A WORKING EXAMPLE OF A SELF-IMPROVING DIAGNOSIS (SID) SYSTEM. THIS SYSTEM WOULD BE USED WHEN A FAILURE CANNOT BE FOUND BY ATE. IT WOULD SUMMON MANUAL TROUBLESHOOTING AND REQUEST A RECORD OF THE SUCCESSFUL REPAIR ACTION. THESE RECORDS WOULD BE USED TO RECOMMEND REPAIR ACTIONS ON FUTURE OCCURRENCES OF THE SAME FAILURE SYMPTOM. WHILE THE TEST MODEL USES ONLY THE RELATIVE FREQUENCY OF SUCCESSFUL FIXES FOR A PARTICULAR SYMPTOM, INFERENTIAL MECHANISMS COULD BE ADDED TO DETECT TRENDS WHICH SUGGEST REVISIONS TO THE STRATEGY DICTATED BY FREQUENCY ALONE.

ALSO PROPOSED BY THE MATE OFFICE IS THE RECORDING BY THE SID OF THE SERIAL NUMBERS OF ALL ITEMS REPAIRED AND THE APPLICATION OF HEURISTICS TO IDENTIFY ITEMS WHICH RETURN TOO OFTEN. THESE WOULD BE FLAGGED AS REQUIRING SPECIAL ATTENTION BECAUSE OF THE POSSIBILITY OF A CHRONIC PROBLEM NOT SOLVED BY THE ROUTINE PROCEDURE. THIS FEATURE NOW EXISTS IN A MARCONI ATE SYSTEM.

6.3. THEOREM PROVING

THEOREM PROVING TECHNIQUES, AS MENTIONED, ARE USED IN AI APPLICATIONS IN THE OTHER FIELDS OF INTEREST LISTED, PARTICULARLY IN EXPERT SYSTEMS. THEIR CONTRIBUTIONS IN THESE APPLICATIONS WILL BE COVERED IN THE APPROPRIATE DISCUSSIONS. THERE IS ONE APPLICATION WHICH IS WELL WORTH NOTING HERE.

BIT SIGNALS ARE TOO OFTEN FALSE ALARMS. IN ADDITION, INTERMITTENT FAILURES ARE DIFFICULT TO DISTINGUISH FROM FALSE ALARMS. THEOREM PROVING TECHNIQUES COULD BE EMPLOYED TO TEST BIT SIGNALS TO DISCRIMINATE AGAINST FALSE ALARMS AND TO IDENTIFY INTERMITTENT FAILURES.

A SIMPLE PROCEDURE WAS USED BY THE F-16 TO EVALUATE BIT SIGNALS. EACH SIGNAL WAS STORED AND THE BIT CHECKED AGAIN AFTER A SHORT TIME. IF FIVE OUT OF SEVEN CHECKS AGREED ON A FAILURE INDICATION, THE BIT LATCH WAS TRIGGERED. SMART BIT WOULD EXTEND THIS TO SUCH ACTIONS AS CHANGING THE DECISION THRESHOLD, ADJUSTING THE BIT SENSITIVITY, AND IDENTIFYING INTERMITTENT FAILURES. SMART BIT SYSTEMS ON INDIVIDUAL WEAPONS SYSTEMS COULD COMPARE THEIR MEMORIES TO IDENTIFY UNUSUAL CIRCUMSTANCES. THE COMPARISON MIGHT, FOR EXAMPLE, SHOW ONE SYSTEM WITH MORE THAN EXPECTED FAILURE INDICATIONS INDICATING SOME PROBLEM WITH THE PLATFORM (EG A FAULTY ENVIRONMENTAL CONTROL SYSTEM). WITH INCORPORATED ENVIRONMENTAL DATA, SMART BIT COULD HELP LOCATE AN IDENTIFIED INTERMITTENT FAILURE. THE BOEING OBIT CIRCUIT AND THE BATTELLE STRESS METER ARE DESIGNED TO RECORD ENVIRONMENTAL DATA AND COULD BE ADDED TO THE SMART BIT. SMART BIT IS CONSIDERED A NEAR TERM POSSIBILITY.

6.4. AUTOMATIC PROGRAMMING

ATPG, MENTIONED ABOVE, CAN BE CONSIDERED AN EXAMPLE OF AUTOMATIC PROGRAMMING. THERE ARE ALSO PROGRAMS WHICH ASSIST A TEST ENGINEER IN CREATING ATLAS STATEMENTS FOR TEST EQUIPMENT, THOUGH THESE ARE NOT

REALLY SOPHISTICATED ENOUGH TO WARRANT THE TITLE. THE ULTIMATE APPLICATION OF AUTOMATIC PROGRAMMING WILL BE THE REAL TIME GENERATION OF ATLAS TEST VECTORS FROM A COMPUTERIZED REPRESENTATION OF THE SYSTEM, AS THEY ARE NEEDED BY AN EXPERT SYSTEM ISOLATING A FAILURE. THIS IS DEFINITELY NOT A SHORT TERM GOAL.

6.5. COMBINATORIAL/SCHEDULING PROBLEMS

WORK IN THIS TOPIC CAN BE USED IN THE NEAR TERM TO DEVELOP MODELS FOR QUEUING MAINTENANCE FOR MINIMUM IMPACT ON SYSTEM DOWN TIME. IT CAN ALSO BE USED TO DESIGN FOR FAULT TOLERANCE OF DISTRIBUTED SYSTEMS SUCH AS COMMAND AND CONTROL SYSTEMS OR FOR FAULT TOLERANCE IN VHSIC CHIPS.

THE ULTIMATE POTENTIAL OF THE TECHNIQUES WOULD BE IN REAL TIME MAINTENANCE SCHEDULING AND IN REAL TIME RECONFIGURATION OF NETWORKS AROUND A FAILED COMPONENT.

6.6. MACHINE PERCEPTION

CURRENT AI PROGRAMS CAN IDENTIFY SHAPES. ON A SIMPLER LEVEL, THE MARCONI ATE MENTIONED ABOVE WILL READ SERIAL NUMBERS MARKED IN BAR CODES, AND OPTICAL CHARACTER READERS ARE AVAILABLE TO READ STYLIZED ALPHANUMERICS. WE CAN THUS EASILY PRODUCE SYSTEMS WHICH WILL READ INFORMATION PRINTED ON A BOARD, BUT THIS WILL BE OF NO USE UNTIL THE ATE IS PROGRAMMED TO MAKE USE OF THE INFORMATION. IN THE NEAR TERM WE CAN ADD AUTOMATION TO ATE LETTING IT CALL ITS OWN TEST PROGRAMS FROM ITS IDENTIFICATION OF THE BOARD. THIS COULD BE OF VALUE IN THAT IT WOULD ELIMINATE SOME OF THE DULLER RESPONSIBILITIES OF THE MAINTENANCE MAN. IN THE LONG TERM, MACHINE PERCEPTION CAN BE USED TO GET FULL VALUE FROM ROBOT SYSTEMS BY RECOGNIZING ROTATIONS AND DISPLACEMENTS OF ITEMS TO BE TESTED, WHICH, WITH AN APPROPRIATE CONTROL PROGRAM, WILL ELIMINATE THE NEED FOR ITEMS TO BE FED TO THE ROBOT IN A RIGIDLY CONTROLLED MANNER. PRESUMING A ROBOT FED ATE SYSTEM, THE AUTOMATIC IDENTIFICATION FEATURES WOULD BECOME QUITE USEFUL, AS THE HUMAN WOULD BE NEEDED ONLY WHEN THE MACHINE REQUIRED INTELLIGENT HELP. WITH AMBULATORY ROBOTS, PERCEPTION COULD BE USED TO LOCATE PARTICULAR BOARDS IN AN EQUIPMENT FOR REMOVAL BY THE ROBOT AND CONVEYANCE TO THE ATE.

6.7. EXPERT CONSULTING SYSTEMS

EXPERT SYSTEMS ARE IN PRACTICAL USE TODAY FOR CONFIGURING COMPUTER SYSTEMS (R1), AND ARE AVAILABLE FOR MEDICAL DIAGNOSIS (MYCIN,CADUCEUS) AND LOCATING MINERAL DEPOSITS (PROSPECTOR). THERE ARE ALSO EXPERT SYSTEMS IN VARIOUS STATES OF DEVELOPMENT FOR FAULT ISOLATION. THESE INCLUDE DELTA FOR THE MAINTENANCE OF LOCOMOTIVES, REACTOR FOR NUCLEAR REACTORS, CRITTER FOR DIGITAL CIRCUITS, IDT USED ON A COMPUTER, AND DART DESIGNED FOR COMPUTER HARDWARE. (SEE ALSO POSITION PAPER BY CAREN ON A GENERIC MAINTENANCE EXPERT, LES). HENCE, MAINTENANCE EXPERT SYSTEMS ARE RELATIVELY NEAR TERM POSSIBILITIES.

THE DIAGNOSTIC SEARCH PROGRAMS (LOGMOD,STAMP,FIND), MENTIONED ABOVE, WOULD SEEM TO BE A VALUABLE ADJUNCT TO AN EXPERT MAINTENANCE PROGRAM IN THAT THEY CAN BE USED BY THE PROGRAM TO SET UP ITS STRATEGY FROM THE DESIGN OF THE UNIT UNDER TEST.

AN EXPERT SYSTEMS REQUIRES A KNOWLEDGE BASE OF ITS DOMAIN. AT PRESENT, THIS IS PROVIDED BY THE USER. LOGMOD, ET AL, REQUIRE USER LAYOUT OF THE SYSTEM AND USER GENERATION OF APPROPRIATE TESTS. THE ULTIMATE EXPERT SYSTEM WOULD USE ADVANCES IN AUTOMATIC PROGRAMMING TO PERFORM FULLY AUTOMATIC TESTING BY DERIVING ITS KNOWLEDGE FROM A MACHINE READ SCHEMATIC, FORMING ITS STRATEGY FROM THAT KNOWLEDGE, AND GENERATING APPROPRIATE TESTS AS IT NEEDS THEM.

ONCE THE ATE HAS THE KNOWLEDGE IT NEEDS TO OPERATE AS AN EXPERT SYSTEM, IT CAN ALSO BE USED AS A MAINTENANCE AID TO DIRECT A HUMAN WHEN HIS INTERVENTION IS NECESSARY. IT COULD ALSO PROVIDE THE INTERACTION NEEDED FOR TRAINING ITS OPERATOR. THUS THE EXPERT SYSTEM WOULD SERVE AS ATE, MAINTENANCE AID, AND TRAINING DEVICE. WHILE PROBABLY NOT A SHORT TERM EFFORT, THE INTEGRATION OF MAINTENANCE AIDS SHOULD NOT BE A FAR OUT PROPOSITION. INTEGRATING A TRAINING CAPABILITY WILL BE A LONG TERM PROPOSITION NEEDING ADVANCES IN COMPUTER AIDED INSTRUCTION (CAI) TECHNIQUES.

COMPUTER AIDED DESIGN (CAD) PROGRAMS CAN BE CONSIDERED A FORM OF EXPERT SYSTEM, EVEN THOUGH THEIR CURRENT APPROACHES MAY NOT BE CONSIDERED TO BE EXAMPLES OF AI. THE ROME AIR DEVELOPMENT CENTER IS STUDYING THE INCORPORATION OF EASE OF TEST CONSIDERATIONS TO CAD PROGRAMS. FROM THESE CAN SPRING AN EXPERT SYSTEM WHICH WHICH WILL CREATE A DESIGN WITH A MINIMUM OF MAINTENANCE PROBLEMS. THIS WILL REQUIRE THE CREATION OF A SET OF DESIGN RULES FOR EASE OF MAINTENANCE AND A SET OF RULES TO TRADE THESE OFF AGAINST OTHER CONSIDERATIONS SUCH AS THERMAL DESIGN, WIRING CONSTRAINTS, ETC. THE DESIGN RULES SHOULD BE A NEAR TERM POSSIBILITY, BUT CREATING THE TRADE-OFF RULES WILL BE A MORE DIFFICULT TASK.

6.8. ROBOTICS

CURRENT USE OF ROBOTS IS MOSTLY AS PROGRAMMABLE MANIPULATORS. AT LEAST TWO COMPANIES HAVE DESIGNED ROBOT MANIPULATORS TO FEED TEST SAMPLES INTO ATE. ANOTHER IMMEDIATE POSSIBILITY IS THE HANDLING OF THE ADAPTERS WHICH FORM THE INTERFACE BETWEEN TEST SAMPLES AND THE ATE, RELIEVING THE HUMAN OF THE NEED TO MANUALLY CHANGE ADAPTERS. NEAR TERM POSSIBILITIES ARE THE USE OF MACHINE PERCEPTION PERMITTING THE ROBOT TO WORK IN AN UNORGANIZED ENVIRONMENT (EG CORRECTLY FEED PRINTED CIRCUIT BOARDS PILED RANDOMLY ON A TABLE.) THE FAR OUT APPLICATION IS THE USE OF AN AMBULATORY ROBOT WITH AN EXPERT SYSTEM TO PERFORM COMPLETELY AUTOMATIC MAINTENANCE.

7.0. CAVEATS

HERBERT DREYFUS, A CRITIC OF AI, DIVIDES INTELLIGENT ACTIVITY INTO FOUR CLASSES. HIS LOWEST CLASS, ASSOCIATIONISTIC (LEARNED BY MEMORY) INCLUDES SUCH EXAMPLES AS MAZE PROBLEMS. THE NEXT HIGHER CLASS, SIMPLE FORMAL (LEARNED BY RULE) INCLUDES GAMES LIKE TIC-TAC-TOE AND THE PROOF OF THEOREMS USING MECHANICAL PROOF PROCEDURES. THESE PROBLEMS ARE EASILY HANDLED BY AI TECHNIQUES. THE HIGHEST CLASS, NONFORMAL ACTIVITIES, (LEARNED BY EXAMPLE) INCLUDES PROBLEMS WHICH DREYFUS SEES NO POSSIBILITY FOR SOLUTION BY AI TECHNIQUES. THESE INCLUDE NATURAL LANGUAGE TRANSLATION AND ILL-DEFINED GAMES SUCH AS RIDDLES. THE REMAINING CLASS IS COMPLEX FORMAL (LEARNED BY RULE AND PRACTICE) WHICH INCLUDES UNCOMPUTABLE GAMES LIKE CHESS AND PROOF OF THEOREMS WHERE NO MECHANICAL PROOF PROCEDURE APPLIES. HERE AI IS MOST DIFFICULT TO APPLY AND THIS IS THE REALM OF MAINTENANCE PROBLEMS. FORTUNATELY, AS THE MANY CHESS-PLAYING PROGRAMS ATTEST, THE DIFFICULTIES ARE NOT INSURMOUNTABLE.

AS WITH ALL NEW TECHNOLOGY, APPLICATIONS OF AI CANNOT BE MADE CARELESSLY. BESIDES THE NATURAL LIMITATIONS AND TECHNICAL CONSTRAINTS, WE MUST CONSIDER THE IMPACT OF AI ON THE MAINTENANCE PERSONNEL. WE SHALL NOW BRIEFLY DISCUSS SOME POTENTIAL TRAPS.

THE NATURAL LIMITATIONS OF AI ARISE FROM THE FACT THAT WE CANNOT BUILD A MACHINE WHICH DUPLICATES THE INTELLIGENCE OF A HUMAN. HENCE, WE CANNOT CREATE A MACHINE WHICH WILL UNDERSTAND NATURAL LANGUAGE, BECAUSE WE CANNOT BUILD IN THE TOTAL EXPERIENCE THAT A HUMAN USES TO INTERPET A MESSAGE. WE CAN ONLY HOPE TO GIVE IT SUFFICIENT ABILITY TO COMMUNICATE IN ITS DOMAIN AND SOME CAPABILITY TO ADD NEW WORDS TO ITS VOCABULARY.

IT WILL BE A LONG TIME, IF EVER, THAT A MACHINE WILL HAVE A TRUE ABILITY TO LEARN. NO PLANS SHOULD ANTICIPATE SUCH A CAPABILITY UNTIL EVIDENCE OF SIGNIFICANT PROGRESS IS AVAILABLE.

IN CREATING EXPERT SYSTEMS BY REDUCING THE EXPERTS OPERATION TO A SET OF RULES, WE IGNORE THE FACT THAT EXPERTISE IS A BEHAVIOR RATHER THAN A SET OF RULES. IF THE RULES WILL SUFFICE, THE SYSTEM WILL BE SUCCESSFUL. IF NOT, WE MUST PROVIDE FOR THE HUMAN TO TAKE OVER AS NECESSARY.

TECHNICAL CONSTRAINTS ON AI INCLUDE PROCESSING TIME AND MEMORY REQUIREMENTS. AI PROGRAMS ARE NOTED FOR FILLING UP LARGE MACHINES. WHILE HIGHER SPEEDS AND LARGER MEMORIES ARE STILL BEING DEVELOPED, PRACTICAL APPLICATIONS MUST RECOGNIZE THE LIMITS. AS AN EXAMPLE, TEN FACTORIAL COMBINATIONS IS NOT A LARGE NUMBER. YET IF THE ANALYSIS OF EACH TOOK 23 MILLISECONDS, THE PROBLEM WOULD REQUIRE 24 HOURS OF MACHINE TIME. AS ANOTHER EXAMPLE, THERE ARE APPROXIMATELY 10 TO THE 50TH POWER ATOMS IN THE EARTH. THIS IS FAR SMALLER THAN THE POSSIBLE NUMBER OF MOVES IN A CHESS GAME. HENCE, THE COMBINATORIAL EXPLOSION IS SOMETHING TO BE AVOIDED IN AI PROGRAMS, AS THE CHESS-PLAYERS DO BY PRUNING THEIR SEARCH TREES.

AI PROGRAMS ARE TYPICALLY BEGUN AS SMALL FEASIBILITY DEMONSTRATIONS. TROUBLE BEGINS, HOWEVER, WHEN ONE ATTEMPTS TO SCALE UP THE PROGRAM TO HANDLE REAL WORLD COMPLICATIONS. HENCE, THE TECHNICAL LIMITS TO AN AVAILABLE TECHNIQUE MUST BE CONSIDERED BEFORE ITS APPLICATION TO A NEW PROBLEM.

FINALLY, IN APPLYING AI TO MAINTENANCE WE MUST CONSIDER THE MAN-MACHINE RELATIONSHIP. DECLINING SKILL LEVELS PROMOTE A TEMPTATION TO FOLLOW A "SMART MACHINE-DUMB MAN" PHILOSOPHY. IF THE MAN IS SUBJECT TO DIRECTION BY A MACHINE WHICH DOES NOT CREDIT HIM WITH ANY CAPABILITY, THEN:

- ANY CAPABILITY HE HAS IS WASTED
- HE WILL NOT IMPROVE IN CAPABILITY
- HE WILL FIND NO SATISFACTION WITH HIS JOB

THE ITEMS LISTED ABOVE ARE NOT ONLY DEMEANING TO THE MAN, THEY CAN CREATE A DANGEROUS WORKING CLIMATE.

FOR THIS REASON, AI APPLICATIONS TO MAINTENANCE SHOULD TO THE GREATEST EXTENT POSSIBLE BE DESIGNED TO ADAPT TO THE SKILL OF THE USER, AND SERVE AS A MEANS TO IMPROVE HIS SKILL. THERE ARE CONSIDERATIONS WHICH CAN BE MADE. INTELLIGENT TRAINERS NOW EXIST WHICH WILL ADAPT THEIR MODE OF OPERATION TO THE NEEDS OF THE STUDENT. THERE IS NO NEED FOR AN EXPERT SYSTEM TO COMMUNICATE BY A FIXED LIST OF QUESTIONS TO THE OPERATOR. IT CAN BEGIN BY ASKING FOR THE OPERATORS FINDINGS AND CONCLUSIONS.

AI SYSTEMS MUST TO THE EXTENT POSSIBLE BE DESIGNED SO THAT THE HUMAN WILL CONSIDER IT AS A PARTNER RATHER THAN AS AN INANIMATE TYRANT FOR WHICH THE HUMAN PERFORMS TRIVIAL FUNCTIONS.

8.0. PRESENT RESEARCH IN AI APPLICATIONS TO MAINTENANCE

A ROUGH ESTIMATE OF FY-83 FUNDING IN AI RESEARCH IS THE RANGE FROM $36 MILLION TO $46 MILLION. OF THIS, DOD AGENCIES ACCOUNT FOR $20 MILLION, AND OTHER U.S. AGENCIES, $6 MILLION. THE MAJORITY OF THESE FUNDS ARE 6.1. INDUSTRY WILL SPEND AN ESTIMATED $10-20 MILLION, WHICH CAN BE CONSIDERED MOSTLY 6.2

OF THESE FUNDS, WE HAVE IDENTIFIED $0.3 MILLION BEING SPENT BY DOD AGENCIES IN STUDIES OF AI APPLICATIONS TO MAINTENANCE, AND THIS AMOUNT IS SPREAD EQUALLY AMONG ~~FOUR~~ THREE STUDIES. THESE ARE:

(1). A STUDY BY THE ROME AIR DEVELOPMENT CENTER TO DETERMINE THE OPPORTUNITIES AND RISKS OF AI APPLICATIONS TO TESTABILITY, AWARDED APRIL, 1983 TO BOEING.

(2). A STUDY BY THE NAVAL AIR ENGINEERING CENTER TO DEVELOP AI APPLICATIONS TO NAVY ATE, AWARD PENDING.

(3). A STUDY BY THE AIR FORCE HUMAN RESOURCES LABORATORY TO ADAPT MEDICAL EXPERT SYSTEMS TO MAINTENANCE, AWARDED FEB, 1983 TO SYSTEMS EXPLORATION.

IN ADDITION, THERE ARE SOME OTHER EFFORTS, SUCH AS AN AFHRL STUDY OF AI APPLICATIONS TO TRAINING, WHICH WILL PROVIDE RESULTS USEFUL TO MAINTENANCE.

IN FY-84, THE MATE OFFICE WILL CONTINUE ITS WORK ON SELF-IMPROVING DIAGNOSTICS, WHICH WAS UNFUNDED IN FY-83. RADC WILL BEGIN AN EFFORT TO DEVELOP DESIGNS FOR SMART BIT. THE AIR FORCE INSTITUTE OF TECHNOLOGY WILL BE WORKING WITH RADC AND WARNER-ROBINS AIR LOGISTIC CENTER TO DEVELOP AN EXPERIMENTAL EXPERT SYSTEM FOR DEPOT MAINTENANCE, AIMED AT SPECIFIC PROBLEMS OF WRALC.

THERE IS A SIGNIFICANTLY GREATER AMOUNT OF INDUSTRY IR/D DIRECTED AT APPLYING AI TO MAINTENANCE. A ROUGH ESTIMATE IS $3 MILLION IN FY-83. THIS DOES NOT INCLUDE CAPITAL INVESTMENTS, SUCH AS GE'S DEVELOPMENT OF DELTA TO AID IN LOCOMOTIVE REPAIR.

IN SUMMARY, CURRENT DOD EFFORTS ARE SMALL AND EXPLORATORY.

9.0. RECOMMENDATIONS TO THE DEPARTMENT OF DEFENSE

DESPITE THE FACT THAT THE MEMBERS OF THE COMMITTEE WORKED COMPLETELY INDEPENDENTLY, THERE IS ONLY ONE AREA OF SIGNIFICANT DISAGREEMENT IN THE POSITION PAPERS. THIS IS THE RECOMMENDED LANGUAGE IN WHICH AI PROGRAMS SHOULD BE WRITTEN. AN AREA OF GENERAL AGREEMENT WAS THAT EXPERT CONSULTANT SYSTEMS CAN, AND SHOULD, BE APPLIED TO MAINTENANCE NOW. THERE WAS EVEN A GENERAL CONSENSUS OF THE DEVELOPMENT RESOURCES REQUIRED FOR AN EXPERT SYSTEM: TWO YEARS TIME, $200,000 IN COMPUTER COSTS, AND FIVE TO TEN MAN-YEARS PER YEAR. HOWEVER, DISCUSSIONS AFTER REVIEW OF THE POSITION PAPERS WOULD CAUSE THESE TO BE CONSIDERED MINIMUM PROJECTIONS, WITH PERHAPS DOUBLE THE COMPUTER RESOURCES AND FIVE YEARS OF TIME REQUIRED. THE FOLLOWING RECOMMENDATIONS ARE THE CHAIRMAN'S CONSOLIDATION OF THE POSITION PAPERS, DISCUSSIONS WITH THE RADC CONTRIBUTORS, AND HIS DERIVATIONS FROM THE INFORMATION GIVEN ABOVE. ALL THE POSITION PAPERS ARE ATTACHED TO THIS REPORT. THE READER IS ENCOURAGED TO REVIEW THEM FOR FURTHER DETAILS.

RECOMMENDATION NO. 1

THE DoD SHOULD TAKE ADVANTAGE OF THE RELATIVE MATURITY OF THE TECHNOLOGY FOR CREATING EXPERT SYSTEMS. SPECIFIC APPLICATIONS OF MAINTENANCE EXPERT SYSTEMS SHOULD BE STARTED IMMEDIATELY, AND MULTI-APPLICATION MAINTENANCE EXPERTS DEVELOPED AND STANDARDIZED.

THE DoD SHOULD IMMEDIATELY DEVELOP EXPERT SYSTEMS FOR EXISTING MAINTENANCE APPLICATIONS WHERE MAINTENANCE IS PARTICULARLY TROUBLESOME. AS AN EXAMPLE, THE AFIT-RADC-WRALC PROGRAM WOULD ATTEMPT TO CREATE A SYSTEM TO WORK WITH THE F-15 ANALOG PRINTED CIRCUIT BOARD TEST STATION. IT WOULD FIRST BE PROGRAMMED WITH THE KNOWLEDGE REQUIRED TO TROUBLESHOOT ONLY ONE BOARD, THE MOST TROUBLESOME OF THOSE THE ATE HANDLES. THIS WOULD SHOW THE VALUE OF THE APPROACH AND PERMIT DEBUGGING OF THE SYSTEM. MORE KNOWLEDGE WOULD BE ADDED INCREMENTALLY UNTIL THE SYSTEM HANDLED EVERY BOARD ASSIGNED TO THE ORIGINAL ATE. AT THIS POINT, IT WOULD HOPEFULLY BE COST EFFECTIVE TO SCRAP THE ORIGINAL SYSTEM. IF NOT, THE EXPERT SYSTEM WOULD STILL EARN ITS KEEP BY ITS SUPERIOR HANDLING OF PROBLEM BOARDS. EACH SERVICE COULD PICK A PROMISING CANDIDATE (A SYSTEM WHICH IS NOT HANDLED WELL BY THE ATE, AND FOR WHICH EXPERT MAINTENANCE PERSONNEL ARE BOTH AVAILABLE AND WILLING TO COOPERATE IN CREATING THE EXPERT MAINTENANCE SYSTEM). AS IT BUILDS AND REFINES THE MAINTENANCE EXPERT SYSTEM, THE SERVICE WOULD IMPROVE THE OPERATIONAL READINESS OF THE CANDIDATE SYSTEM WHILE IT GAINS EXPERIENCE AND CONFIDENCE WITH THE AI TECHNOLOGY. NO RISK WOULD BE INVOLVED, SINCE THE EXISTING ATE WOULD STILL BE IN PLACE. RESOURCES WOULD BE TWO TO FIVE YEARS CALENDAR TIME, 10-20 MANYEARS OF EFFORT AND $200,000 TO $500,000 IN COMPUTER COSTS FOR EACH SYSTEM. EACH SYSTEM WOULD PAY FOR ITSELF IN SHORT ORDER, BY REDUCING MAINTENANCE TIME AS MUCH AS 50%. HOWEVER, THE REAL VALUE OF THESE FIRST EFFORTS WOULD BE IN THE KNOWLEDGE GAINED. (SEE POSITION PAPERS BY FRIEDMAN, BRAUDE, DENICOFF, HONG, CAREN, GENET)

To permit immediate application, the first AI maintenance systems should be built in the language and architecture most convenient to the builder and user, with a blanket exemption from any current policies on languages. The only exception would be that any test sequence generated by the system for outside use would be in ATLAS. No cost involved. Will cause a proliferation of languages for first systems, but will permit earlier implementation, by years, and provide information needed for ultimate standardization. (Chairman's recommendation based on conflicting inputs in position papers by Friedman, Hinchman, and Caren)

To improve cost-effectiveness in the longer term, the DoD should develop versatile maintenance experts for specific domains, such as digital electronics, which are used in many different systems. They would contain the necessary theory and diagnostic strategies for their specific domains. They must be user friendly (interact in a subset of English, explain their actions, and adapt to the skill of the user), and, presuming progress in computer aided instruction (CAI) techniques, each system could ultimately serve as an integrated ATE, maintenance trainer and training aid. One basic system (for one domain) could be built in two years with 10 manyears effort. System specific data bases would be incorporated during the development of the systems to be tested. Refinements would be added as developed. Benefit would be the elimination of the need for reinventing the engine for every application, easily worth millions in development and training savings. Technical risk is moderate. (See position papers by Caren, Braude, Friedman)

Further improvements in cost-effectiveness would be made possible by developing a system building tool to automate the creation of the system specific data required by the expert system discussed in the preceding paragraph. The tool would extract the needed knowledge either from a human expert or, ideally, from a description of the system to be tested. This will minimize one of the major costs of the expert system. Cost would be about $200,000 a year in computer costs and ten manyears per year. A prototype could be available in two years, but it might take a five year program to complete a supportable product. Benefit would be significant savings in time and elimination of errors for every new system to which it is applied. No more than five applications, if that much, would repay the costs with a dividend in earlier test system availability and easier modification as the design of the system under test changes. Technical risk is presently considered high. (See position papers by Hinchman, Hong.)

NOTE: The expert systems would eliminate the long test programs now used in conventional ATE. This feature can be incorporated into conventional ATE systems. To do so the DoD could prohibit all new ATE systems to use inflexible sequential test procedures. Instead require the use of segmented test programs which are called out in the order needed for most rapid fault isolation using the strategies now available in LOGMOD, STAMP, and FIND. Cost will be a significant increase in effort required to program the ATE and some additional memory. Will probably permit the elimination of one maintenance shift, paying for itself in one year or two. (Chairman's recommendation)

RECOMMENDATION NO. 2

DEVELOP "SMART" BIT FOR DIGITAL ELECTRONIC SYSTEMS TO MINIMIZE FALSE ALARMS, IDENTIFY INTERMITTENT FAILURES, IMPROVE COVERAGE OF BIT. AN RADC PROPOSED FY-84 EFFORT HOPES TO PROVIDE DESIGN CONCEPTS WHICH COULD BE USED BY INDIVIDUAL DESIGNERS TO CONSTRUCT SMART BIT IN THEIR PARTICULAR APPLICATIONS. A COMPLETE SERIES OF STUDIES LEADING TO THE DESIGN OF AN ON-BOARD KNOWLEDGE BASED MONITORING SYSTEM OR THE DESIGN AND TEST OF EXPERIMENTAL BIT SYSTEMS COULD RUN TWO TO FOUR YEARS AND ONE TO SIX MILLION DOLLARS. BENEFITS ARE INCALCULABLE SINCE THEY INCLUDE THE WORTH OF REDUCED MISSION ABORTS DUE TO FALSE ALARMS. MORE TANGIBLE BENEFITS COULD BE A 90% REDUCTION IN FALSE ALARMS, AND THE DECREASE OF THE PORTION OF UNITS SENT TO REPAIR WHICH TEST GOOD, FROM THE PRESENT 30% TO PERHAPS 10%. A SUCCESSFUL APPLICATION SHOULD PAY FOR ITSELF IN TWO YEARS OF OPERATION ON ONE SYSTEM, AND PROVIDE A MEASURABLE IMPROVEMENT IN THE READY RATE OF THE SYSTEM USING IT. (SEE POSITION PAPERS BY HONG, BRAUDE.)

RECOMMENDATION NO. 3

FUND APPLIED RESEARCH AND DEVELOPMENT OF AI FOR MAINTENANCE, BOTH TO IMPROVE THE CAPABILITIES OF MAINTENANCE EXPERT SYSTEMS AND TO APPLY AI TO OTHER MAINTENANCE APPLICATIONS. SOME SPECIFIC TOPICS ARE:

1. AUTOMATING THE CREATION AND PRESENTATION OF TECHNICAL MANUALS. (SEE POSITION PAPER BY DENICOFF.)

2. APPLYING AI TO MAINTENANCE INFORMATION SYSTEMS AND DATABASES. (SEE POSITION PAPERS BY BRAUDE, DENICOFF, GENET, HONG.)

3. DEVELOPING CRISIS ALERTING SYSTEMS. (SEE POSITION PAPER BY DENICOFF.)

4. FOR EXPERT MAINTENANCE SYSTEMS, DEVELOPING REQUIREMENTS FOR LANGUAGES AND COMPUTER SYSTEMS, TECHNIQUES FOR IMPROVING USER FRIENDLINESS, AND MORE SOPHISTICATED APPROACHES (EG MEANS OF FORMING RULES FROM THE CIRCUIT ITSELF RATHER THAN FROM AN EXPERT FAMILIAR WITH THE CIRCUIT). (SEE POSITION PAPERS BY BRAUDE, HONG.)

5. DEVELOPING AI SYSTEMS FOR AUTOMATIC TEST PROGRAM GENERATION (ATPG). THE CURRENT AI PROGRAMS USED TO DEVELOP TEST PATTERNS FOR DIGITAL COMBINATORIAL LOGIC SHOULD BE EXTENDED TO SEQUENTIAL LOGIC AND ANALOG CIRCUITS. SYSTEMS SHOULD WORK FROM THE CIRCUIT DESCRIPTION AND PROVIDE TEST VECTORS IN ATLAS. (SEE POSITION PAPERS BY HONG, BRAUDE.)

6. APPLYING AI TECHNIQUES TO VLSI,VHSIC DESIGN FOR FAULT TOLERANCE AND TESTABILITY. THIS SHOULD BE INCORPORATED INTO THE VHSIC PHASE THREE STUDY PLANS. (SEE POSITION PAPER BY HONG.)

7. DEVELOPING KNOWLEDGE BASED COMPUTER AIDED INSTRUCTION (CAI) SYSTEMS FOR MAINTENANCE TRAINING. (SEE POSITION PAPER BY HONG.) NOTE: THIS COULD ULTIMATELY BE INCORPORATED INTO THE ATE ITSELF.

8. DEVELOPING SELF-IMPROVING DIAGNOSTICS AND TEST PROGRAM SETS. (SEE POSITION PAPER BY BRAUDE, AND DISCUSSION OF MATE EFFORT IN PARAGRAPH 6.2 ABOVE.)

OTHER TOPICS WILL BE IDENTIFIED BY THE FY-83 STUDIES BEGUN BY RADC, NAEC, AFHRL. RECOMMEND 6.2 PROGRAMS BE STARTED BY ALL THREE SERVICES, FUNDED AT ONE MILLION DOLLARS PER SERVICE PER YEAR, TO BEGIN WORK. PROMISING DEVELOPMENTS SHOULD BE FOLLOWED BY 6.3 PROJECTS WITH APPROPRIATE HIGHER FUNDING.

RECOMMENDATION NO. 4

FOSTER AN INTEGRATED DOD-INDUSTRY APPROACH.

COORDINATE THE VARIOUS EFFORTS OF DOD AGENCIES THROUGH A TRI-SERVICE GROUP ON AI APPLICATIONS TO MAINTENANCE. RECOMMENDED GROUP WOULD BE A COMMITTEE UNDER THE JLC AUTOMATIC TESTING PANEL. IT COULD ALSO BE UNDER JDL WORKING GROUP FOR AI, BUT SEEMS MORE APPROPRIATE FOR THE AUTOMATIC TESTING PANEL BECAUSE OF ITS INTERFACE WITH OTHER COMMITTEES. PARTICIPANTS WOULD INCLUDE ALL SERVICE AGENCIES INVOLVED TO SHARE RESPONSIBILITIES AND AVOID DUPLICATION OF EFFORTS. IT WOULD ALSO PROVIDE A CONTACT POINT FOR DOD AND INDUSTRY. (CHAIRMAN'S RECOMMENDATION)

ENCOURAGE PRIVATE AVENUES OF DEVELOPMENT OF AI APPLICATIONS TO MAINTENANCE: CONTINUE TO SUPPORT INDUSTRIAL IR/D IN THE AREA, EXPRESS DOD INTEREST AT APPROPRIATE MEETINGS, PROVIDE COPIES OF THIS REPORT TO INDUSTRY. THE NSIA TESTABILITY COMMITTEE, WHICH PARALLELS THE JLC PANEL, SHOULD BE ENCOURAGED TO CREATE A SUBGROUP ON AI APPLICATIONS TO SERVE AS AN INDUSTRY FOCAL POINT. THE CLOSE WORKING RELATIONSHIP OF THE NSIA COMMITTEE AND THE JLC PANEL WOULD BE A NATURAL AVENUE FOR CREATING A DIALOG ON AI APPLICATIONS. (CHAIRMAN'S RECOMMENDATION.)

ATTACHMENTS

POSITION PAPERS

ERIC J. BRAUDE

R. P. CAREN

MARVIN DENICOFF

LEONARD FRIEDMAN

RUSSELL M. GENET

J. H. HINCHMAN

ROBERT HONG

RELIABILITY AND MAINTAINABILITY
POSITION PAPER

INTRODUCTION

Many important aspects of Reliability and Maintainability require reasoning about incompletely defined circumstance, often with inconsistent evidence. Artificial Intelligence provides for the computerization of tasks of this type; as well as providing an "understanding" interface to the more mechanical tasks, allowing the power of the machines to be more effectively employed in the quest for improved R&M. Three areas of potential applications are outlined.

1. DELIVERING TROUBLESHOOTING EXPERT SYSTEMS CONCURRENTLY WITH THE SYSTEMS

In many cases when a contractor develops equipment, the contractor accumulates a data base of experience with failure modes, critical maintenance paths, and reliability data which is supposed to be captured in BITE (built-in test equipment) and in maintenance manuals. Much of this expertise and the associated rules-of-thumb could be captured in an expert system. In addition, there are unacceptable false alarm rates (e.g. 40%) associated with built-in test equipment (BITE). The particular applicability of expert system technology to the false alarm problem is explored further in position paper #5.

a. Recommended DoD Action

Study the feasibility of requiring from contractors the following type of item: an adaptable, easily expandable expert system (computer program) whose purpose it is to trouble-shoot the equipment being delivered by the contractor.

Eric J. Braude
RCA

3/7/83

b. Suggested Approach

i. The DoD should experiment with retro-fitting this idea to some sample existing systems, including attention to false alarms.

ii. Assuming favorable results, the DoD should require from sample projects a paper version of an expert system applicable to the maintenance of the delivered item. Some questions: at what maintenance level are expert system approaches useful; how are they to be specified?

A cost comparison should be made to allow cost/benefit analyses of approaches which integrate more or less expert system technology.

iii. The above step could be repeated for a new project, but the knowledge formatting requirements could be more formal so as to make them closer to those that would be required by a real expert system knowledge base. An important question to be addressed is, "how should the expertise be collected?".

iv. In parallel with the above three efforts, appropriate expert system-building tools could be identified. Special attention could be given to make the knowledge acquisition process easily accessible by a contractor not necessarily familiar with expert systems.

v. In its final state of maturity, the contractor could be paid to deliver a working expert system at the same time as the deliverable equipment. The expert system could then be run concurrently with operational use of the equipment which it maintains.

c. Estimated Time to Completion and Cost (Very Rough)

Stages (i) through (iv) - two years for projects at $200K each. The last phase would cost approximately 5-15% of the cost of the project itself. Much would depend on the efficacy of the expert system building tools.

Eric J. Braude
RCA

3/7/83

d. Impact on Operational Readiness

(1) Advantages

Significant decrease in the span between system delivery and operational readiness maturity.

Improved understanding of the system under use.

(2) Disadvantages

Increased initial cost in system development

e. Technological Risk

- o Possibility that expert system technology may fail as a solution to the maintainability problem.
- o Possibility that current and projected technology cannot achieve expert system building tools which are usable by system developers.
- o An underestimation of percentage increase in costs and schedule associated with the expert system add-on effort.

2. AUTOMATIC TEST PROGRAM GENERATION

The generation of test programs--whether to be run on-line or off line--is extremely time-consuming, expensive and error prone. New ways must be found to generate test programs.

a. Recommended DoD Action

The DoD should encourage research and development in methods to generate test programs based on:

(1) formal descriptions of the unit under test, or

(2) functional, performance, and anticipated failure modes of the unit.

These inputs would be processed by an independent processor which generate a suite of test programs for the unit.

b. Suggested Approach

(1) A study should be commissioned to collect the results of existing approaches to this kind of problem.

(2) The existing efforts should be analyzed to identify missing capabilities. R&D should be funded to address these missing capabilities.

(3) Efforts should be funded to try out the most promising methods on existing systems in laboratory environments so as to compare them with test program generation methods.

(4) Several knowledge-based processors of the type described should be commissioned by the government for use in common areas such as the testing of standard kinds of circuits.

(5) These knowledge-base processors will become GFE on contracts requiring test program generation.

c. Estimated Time to Completion and Cost (Very Rough)

Year 1	$300K
2	$700K
3	$1.5M
4	$1.5M

d. Impact on Operational Readiness

(1) Advantages

Considerable saving to the government in costs of programming test programs.

Reduction in time wasted running irrelevent tests. Ability to cope with uncertainty (especially in analog testing).

(2) Disadvantages

Risk of developing a new programming system and cost of running it.

e. Technological Risk

- o Uncontrolled costs in knowledge-base acquisitions
- o Inability to adequately describe functionality of equipment within feasible knowledge-base technology
- o Waste due to lack of experience in trading off costs of hand-coded tests versus expert system construction costs.

3. ADAPTABLE SPARING SYSTEM

Readiness is heavily influenced by sparing procedures. Sparing database technology is often utilized. In reality, however, many factors affect sparing which are currently not considered computerizable; such as aircraft availability, bottlenecks, and weather crises.

a. Recommended DoD Action

The DoD should encourage the use of data base mechanisms which allow for uncertainty factors. There are several efforts under way, especially within the academic community, to insert a level of intelligence between the user and the data base. For example, in an initial state, a part might be readily available from an expert depot. As time progresses, however, the system could permit the entering of uncertainty factors which would degrade the availability of the part.

b. Suggested Approach

This would be almost identical to 2b.

c. Estimated Time to Completion and Cost

This would be almost identical to 2c.

d. Impact on Operational Readiness

(1) Advantages

The insertion of layers of intelligence will have the effect of automating more of the human effort required in sparing. This leaves readiness personnel more time to consider factors which are known to be beyond the scope of the decision aid system.

(2) Disadvantages

Changes like the ones proposed always cause doubts about the system's value because they leave to machines those functions which are traditionally performed by humans. The responsibility for decisions is thereby weakened.

e. Technological Risk

Even though systems approaching these capabilities have been built, their free-form nature leads to doubts about whether such systems can be properly bounded or even specified. In addition, much work needs to be done on understanding commonality across domains. For example, can a readiness system for one aircraft be easily modified to serve another?

4. AI APPLICATIONS IN BITE MAN-MACHINE INTERFACE

The complexity of Built-In Test Equipment (BITE), as well as the near-term application of (knowledge-based) expert system principles to BITE, will require the ability to effectively exchange information across a "friendly" man/machine interface. Artificial Intelligence techniques can help make this interface friendlier by embedding a layer of intelligence and/or natural language facilities.

a. Recommended DoD Action

DoD must address the extension of human engineering to system complexity at the man/machine interface believed to be a significant factor in personnel recruitment, training, and retention problems in all of the services.

b. Suggested Approach

Almost identical with 1b.

c. Estimated Time to Completion and Cost

Similar to 1c.

d. Impact on Operational Readiness

(1) Advantages

A well-designed synergistic man/machine interface will be unambiguous to all of the system's users, regardless of role, background, or level of expertise (e.g. low aptitude vs. high aptitude; urban vs. rural background; novice vs. expert, etc.). The system will tailor its service requests and explanatory capabilities by adapting to the user's level of understanding. Training will be an inherent part of the military system (tank, EW analysis center, ATE, etc.) because it will act as both a skill enhancer and retainer when not being operated in its primary role. All of these factors will foster a greater acceptance of the system(s) by the user community because they will be tolerant of human error, adapt to style and need, be capable of giving the user the perception that he/she is in control, and allow the user to easily visualize an operationally meaningful model of the processes present in the system.

(2) Disadvantages

An improved man/machine interface will effect both a greater initial system-development cost, as well as a greater per-system cost due to the use of graphic displays, and so on. (These costs are dwarfed by the advantages afforded by the improved interface that is being proposed.)

e. Technological Risk

There is no perceived technological risk in applying human engineering to these systems. (A much greater loss will take place if this technology is not utilized because eventually one may be left with mammoth systems that are unusable because of their complexity.)

5. APPLICATION OF ARTIFICIAL INTELLIGENCE TO THE FALSE ALARM PROBLEM

An unacceptably high false alarm rate (e.g. 40 per cent) exists in many systems which incorporate Built-In-Test-Equipment (BITE) according to the DSB 1981 Summer Study Panel on Operational Readiness with High Performance Systems. Indeed, any system of sufficient complexity is nearly certain to generate false alarms requiring human intervention. There is, therefore, a need to use diagnostic aids with the greatest naturalness so that fault indicators and their soundness can be understood. (Conventional approaches typically require the presence of a quite knowledgeable trouble-shooter to identify false alarms. Several existing expert systems have demonstrated an unmatched ability to answer questions with the appropriate level of detail (MYCIN, AL/X, etc.) and, thereby, accommodate varying levels of user skill.

a. Recommended DoD Action

The DoD should encourage research and development in improving the "explanation subsystem" of expert systems with an emphasis towards ease of use including:

(1) efforts towards improving current models of the level of sophistication of the user,

(2) modeling what the particular user has learned already,

(3) closer accounting of the time spent searching answers to various critical-path questions, and

(4) anticipation of user questions based on past sessions so that near-critical-path questions will be anticipated and some preliminary work performed.

b. Suggested Approach

(1) A study should be commissioned to collect the results of existing approaches to constructing user models and employing these models to perform work on anticipated questions.

(2) Existing efforts should be analyzed to identify missing capabilities. R&D should be funded to address these missing capabilities.

(3) Efforts should be funded to try out the most promising methods on existing systems in laboratory environments.

(4) New explanatory BITE systems should be funded.

c. Estimated Time to Completion and Cost (Very Rough)

Year 1	$300K
2	$400K
3	$1M
4	$1-3M

d. Impact on Operational Readiness

(1) Advantages

Discovery of serious false alarms in a shorter amount of time and far faster isolation of the source of these alarms to prevent recurrence.

Includes self maintenance derived from knowledge based expert system principles. The Built-In-Test would support the maintainer in troubleshooting, accept his conjecture as to the problem cause, suggest additional tests, explain the rationale for the test sequence and final diagnosis. Note that this is another way to embed training.

(2) Disadvantages

The possibility of excessive use of computer resources spent modeling potential user questions.

Eric J. Braude
RCA

Sometimes too verbose.

e. Technological Risk

- o difficulty of user-modeling
- o few or no existing systems have had to model near-critical-path question/answering.

Eric J. Braude

RCA 3/7/83

RCA

Mr. Anthony Coppola
RA^C/RBET
Griffiss AFB, NY 13441

Dear Tony: 10 March 1983

I have been discussing the application of Artificial Intelligence to improve the materiel readiness posture with several RCA people over the last few weeks.

The position paper which I submitted, entitled "Reliability and Maintainability" is my transcription of discussions which I held with Tom Carver of RCA's Automated Systems in Burlington, Mass. Tom's draft of that discussion was delayed in our internal mail, and so I did not have time to reconcile his transcription with mine. I am, therefore, enclosing it with this letter in the expectation that it will usefully contribute to the project.

A sixth position paper, entitled, "Self Adaptive Test Program Sets" is also submitted herewith.

Sincerely,

E. J. Braude

Eric J. Braude, Manager
Software Technology Laboratory

/ab

Copies to Mr. Anthony J. Feduccia
Mr. James R. Feller

4 a. DEVELOP ATE MAN-MACHINE INTERFACE WHICH ADAPTS TO USER SKILL LEVEL

a. Recommended DoD Action

Develop an efficient operator interface which recognizes that ATE operators represent a wide sprectrum of skill levels and that this interface is a source of errors contributing to reduced machine availability.

b. Suggested Approach

The man-machine interface for typical ATE systems is a CRT and keyboard. This interface is used to control the ATE, define the test problem, guide manual intervention in the test procedure and maintain the ATE. The 1981 Defense Science Board Study Panel on Operational Readiness expressed the following:

"System complexity at the man-machine interface (particularly involving the maintainer) is causing personnel recruitment, training and retention problems in all the services".

Suggested approach is to:

- Define the information exchange across the ATE man-machine interface.
- Develop the range of interaction needed to operate and maintain the ATE.
- Develop approaches for more efficient communication of the above information/interaction.
- Examine current and projected display/input technology for application to this problem.
- Explore approaches to sense operator skill level and modify the interface accordingly.
- Modify an existing ATE interface for use as a test bed. As a control experiment modify the ATE power up/power down sequences to incorporate the candidate man-machine approaches.
- Modify the selected ATE self-test diagnostic logic to incorporate new approaches and lessons learned for first experiment.

c. Estimated Time to Completion Cost

One year of accomplished power up/power down sequence, one year to accomplish revised ATE self test experience. Step 1 will required $20K material, two man-years engineering. Step 2 would required $10K material/computer time and two man-years engineering.

d. <u>Impact on Operational Readiness</u>

(1) Advantages

- Positive impact on personnel recruiting, training and retention

- Reduces operator errors

- Improved ATE availability

- Improved test system thru-put

(2) Disadvantages

- Probable increase in ATE unit cost.

e. <u>Technological Risk</u>

- Man-machine interface may be too subtle to accomplish the machine hardware/software adaptation to skill levels. May be necessary to define some number, - e.g., three to five of specific skill levels.

- Hardware implementation of improved man-machine interface may pose reliability problems in military field environment.

6. SELF ADAPTIVE TEST PROGRAM SETS

a. Recommended DoD Action

Develop ATE application software which can learn from test experince to improve test and diagnostic efficiency.

b. Suggested Approach

Test Program Sets (TPS) represent the greatest non-recurring investment associated with automatic test equipment. These TPSs, once fielded, continue to perform tests in the same sequence with the same diagnostic logic unless they are modified through a costly and time consuming process. As a result TPSs are only modified (1) to correct errors in the program, (2) in response to modifications in the unit-under-test or (3) in response to modifications in the test system.

There is another class of information available which could be used to improve the efficiency of the TPSs. As a result of having run TPSs, the test system develops out-of-tolerance data, identifies faulty subassemblies and components, and could develop prognostic trends from test results on like items tested. An expert technician would use this test history to alter the test sequence to look for likely failure sources first or by-pass lengthy tests which have been ineffective in identifying faults. In short, he would learn to make the test process more efficient approach:

- Choose a sample of ten ATE test programs.
- Examine the go-chain and where in the go-chain the diagnostic logic is initiated.
- Assume a skewed distribution of failures - different from that on which the TPS development was based.
- Develop software which recognizes failure 'epidemics' and modifies TPS accordingly.
- Examine test/diagnostic efficiency improvement accomplished by adaptive program.

c. Estimated Time to Completion and Cost

One year - two man-years engineering
- $5K computer time

d. Impact on Operational Readiness

(1) Advantages

- Improved Test/diagnostic productivity
- Potential Introduction of prognostic capability

(2) Disadvantages

- Increases TPS software complexity

e. <u>Technological Risk</u>

- Adaptive software will be inherently difficult to debug.

Lockheed
PALO ALTO
RESEARCH
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3251 HANOVER STREET · PALO ALTO, CALIFORNIA · 94304

4 March 1983

Department of the Air Force
Headquarters Rome Air Development Center
Mr. Anthony Coppola
RADC/RBET
Griffiss AFB NY 13441

Dear Mr. Coppola:

This is in response to your letter of 7 February 1983, requesting our participation on a committee to recommend Artificial Intelligence applications to maintenance and testing. We are pleased to participate in this exercise.

Lockheed's Palo Alto Research Laboratories, and other parts of Lockheed Missiles & Space Company, are studying AI applications in the areas of expert systems for field maintenance and test of military systems and tactical data fusion; image understanding for smart sensors and guidance/navigation; automation of manufacturing, inspection, and software development and documentation; and computer assisted instruction. We feel therefore that we are in a reasonably knowledgeable position to comment on the utility of AI in an application sense.

The remainder of this letter addresses the question of AI application to maintenance and testing of military equipment. It is in the format suggested by the attachment to your letter:

- 0 Recommended AI Application to Maintenance & Test
- 0 Approach
- 0 Estimated Time to Completion, and Cost
- 0 Impact on Operational Readiness
- 0 Technological Risk
- 0 General Comments:
  - 0 Potential Roadblocks to Development & Application
  - 0 Speech Recognition & Synthesis for Greater Friendliness
  - 0 Use of Medium-Expert Systems
  - 0 Use of the Maintenance Expert System as an Aid to O.R.
  - 0 Other Lockheed Investigations Related to Expert Systems

Briefly, we recommend that DoD promote the development and application of generic expert maintenance systems to a wide variety of military hardware. This is because of the very nature of the DoD maintenance problem, namely, many similar items of a particular equipment class, in geographically diverse sites, need to be maintained in a high degree of readiness with a fairly unskilled labor force. Additionally, with the manpower limits faced by the services this labor force must be as productive as possible. The answer would seem obviously to be the availability of diagnostic and maintenance experts to help the field technician over his major hurdles. Thus, what is called for is a skilled set of technicians who are universally available, have the most updated knowledge, and do not add significant manpower or other elements of cost. A computer based expert system satisfies these criteria, as it is relatively cheap (its development costs are amortized over the number of similar types of equipment and it could run in a machine like LISA), can be easily updated, can be as good as required, and provides uniform standards. Although the first such systems, tailored to a few specific items of equipment, will be rather expensive, their generic nature will make the subsequent tailoring to other specific items straightforward and cheap.

It is quite timely for such activity to begin now. Expert systems have already proven cost effective in medical (especially cancer) diagnosis and treatment (Stanford University and NIH), and in oil exploration (Exxon), and will be employed later this year for troubleshooting malfunctioning diesel-electric locomotives (GE). The impact of such a maintenance approach can be measured in terms of operational readiness, where it can result in lower skill and training requirements, lower manpower requirements, higher morale, and a general improvement in the speed and accuracy of trouble-shooting and fault finding. (These are items 2,3, and 6 of the Technology Selection Criteria contained in John Rivoire's letter to me of 18 January 83.) In addition, it is conceivable that a variant of the maintenance expert system can be used as an aid in operations research to improve the capability to project and analyze the impact of reliability and maintenance (design/cost) on operational readiness. (See under General Comments below -- this is item 11 of the Technology Selection Criteria.)

RECOMMENDED AI APPLICATION TO MAINTENANCE AND TEST:

We recommend that the DoD promote the investigation, development, and application of expert system methods to the maintenance and test of broad classes of military equipment and systems of interest, and the use of expert systems that are tailored for specific equipment as a training aid for maintenance technicians. At LMSC we are considering applying such methods to field maintenance of Navy Trident and Army RPV -- military systems we are most familiar with -- and will eventually be evaluating the potential of applying these methods to military aircraft with our sister company, Lockheed Georgia. Use of the expert system as part of a training module is being considered as well.

APPROACH:

Attachment 1 describes the Lockheed Expert System (called LES) in text form; Attachment 2 is a viewfoil distillation. LES is, roughly speaking, divided into a friendly inference engine and an independent knowledge base. Currently, LES is "written" (the inference engine is complete), but "empty" (the knowledge base is blank as far as military systems go). To give a specific example of its use, but to avoid classification problems, we have demonstrated its use for car maintenance and repair by filling the knowledge base from a standard GM car repair manual -- this example can be seen in Attachments 1 and 2. The system is coded in PL/I, which is a more standard and efficient language than LISP, and has better string structure than PASCAL or FORTRAN. It is thus quite portable, and can be fitted into an 8086 microprocessor. However, there is no reason that the system could not readily be converted to one of the more accepted AI languages such as LISP or a LISP variant, or PROLOG.

ESTIMATED TIME TO COMPLETION, AND COST:

For a typical application on a system like Trident, we estimate that about five man-years total effort and roughly $100K of computer cost would be required to fill the knowledge base with Trident parameters and verify that the procedures meet specs; this effort and cost would probably be distributed over two years. (Exact effort, cost, and time would depend on the scope of the application.) Although it is difficult to say, we would guess that roughly the same effort, cost, and time would be required for, say, C-5 or Hercules. Cost and effort for RPV probably would be half that for Trident, but would have to be distributed over a longer period since the RPV is not as mature or field-tested, and a maintenance/test methodology is not fully developed yet.

IMPACT ON OPERATIONAL READINESS:

Relative to maintenance performed using conventional paper manuals, we expect use of the friendly expert system to decrease costs, increase technicians accuracy and speed, and improve morale. LES draws conclusions from the answers that the techician provides to its questions, and if questioned itself can explain the reasoning process used to arrive at its conclusion by exhibiting in English text the appropriate sections of its extensive if-then program flow. Thus, in addition to being considerably faster and less tedious than skipping through a hefty manual of procedures for each of a number of maintenance protocols, it can increase the confidence of the technician in the (his) diagnosis and possible treatment of problems, and can educate him to the "logic and physics" of the connections between certain symptoms and certain parts of the equipment under test. LES relates faults to test results or to characteristics of the equipment, as appropriate, and can spell out the implications and seriousness of test results or equipment problems. When a piece of analysis has reached a dead end, LES can request specific additional information from the user and tell the user why it needs it. LES keeps a running status of the diagnosis, and can itself be updated and upgraded readily; and if the knowledge base is created and enriched by several experts over a period of time (by the addition of rules), the expert system can become more thorough than any single human expert. The net result of improved technician accuracy, speed, and morale (through real-time "education" as well as relief from paper-flipping tedium) will be increased operational readiness per dollar.

TECHNOLOGICAL RISK:

Technological risk associated with LES application to maintenance and test appears to be very small. Division of LES into an inference engine and a knowledge base means that the inference engine portion is not system peculiar -- essentially only the knowledge base has to be changed for LES to be applicable to other particular military systems, so the maintenance/test use capability appears to be quite generic. Because of the extensive use of "if-then" rules, the writing of new knowledge bases, starting from an already prepared paper manual, is quite straightforward. LES is written in PL/I G (General Purpose) subset, proposed ANSI Standard BSR X3-74; thus it is portable, and easy to interface to other programs in FORTRAN or PASCAL. (It would have been more difficult to develop in Ada since standard Ada does not have a character string variable, but it can be machine translated to Ada if necessary.)

GENERAL COMMENTS:

0 Potential Roadblocks to Development & Application -- AI technology and microprocessor availability are now at the level where application of expert systems to maintenance of complicated military hardware is a realistic near-term goal. Indeed, expert systems have already proven cost effective in medical (especially cancer) diagnosis and treatment, and in oil exploration, and are to be employed later this year for diesel electric locomotive repair. Currently a potential roadblock to aggressive investigation of this capability in the military arena may be the skepticism of military managers about these techniques and their value. Indeed, it is very difficult in abstract discussion to explain why "something that an 18-year-old can do by wading through a manual" can perhaps be more effectively done using a computerized expert system. We believe that the live demonstration of a few specific working models -- even in trivial applications like car repair -- is far superior to abstract discussion for conveying an understanding and appreciation of what's new, different, and potentially better about this maintenance approach than previous ones. And there will undoubtedly be resistance within the defense-related industries to take the initiative and commit to full scale development and application of the expert systems approach, until the military managers are convinced of its promise and simplicity -- perhaps to the point where they begin raising standards and ask for computerized maintenance manuals to accompany new systems and equipment.

0 Speech Recognition and Synthesis for Greater Friendliness -- It is not premature to be considering as well the possibility of incorporating into the expert system such other near-term AI-related technologies as speech (spoken number/yes/no/clear/repeat/next/why, etc.) recognition to free the technician's hands, or speech synthesis to free the technician's eyes. There are already available from such outfits as Interstate Electronics and Telesensory Speech Systems speech recognition modules and speech synthesis modules of highly impressive capability that can be plugged right into terminals. However, there is still a surprising amount of skepticism about the maturity of this technology on the part of people who have actuallv used it, and view of this we would recommend that the advertisement of such "futuristic bells and whistles" be kept to a minimum during the live demonstration referred to in the previous paragraph, unless the modules are present on the expert system being demonstrated. In any case, it should be clear that the intelligence and expertness of the system is independent of this optional enhancement of user friendliness.

0 Usefulness of Medium-Expert Systems -- An expert system need not even be terribly "expert" before it can be useful. For example, use of a terminal with a computerized procedure map can considerably lower the risk of error due to losing one's place on a bedsheet-sized procedural flow chart or any of a number of subordinate charts; use of a system that can record and list the paths followed and remedies performed can considerably reduce the time and tedium associated with the writing of maintenance reports.

0 Use of the Expert System as an Aid to Operations Research -- It is conceivable that by incorporating figures relating to individual component MTBFs and individual component reliability/cost correlations into a subset of the maintenance expert system's knowledge base, an operations analyst would be able to use a variant of the expert system to rapidly (automatically) explore a plethora of interrelated hardware reliability-vs.-cost trades, measuring the impact of each on operational readiness and net (hardware plus maintenance and repair) cost, until he arrives at an optimal point of minimum net cost for a given required level of operational readiness. At Lockheed we are only beginning to investigate this possible application of a maintenance expert system. (Incidentally, some interaction with operations research personnel is highly desirable during the development of the maintenance expert system anyway, since it is handy for the expert system to have some idea of the likelihood of a particular fault and some idea of what is easy to test for in order for it to guide the technician in the most cost-effective manner.)

0 Other Lockheed Investigations Relating to Expert Systems -- Lockheed's approaches to the tactical data fusion area and to the smart sensor and guidance/navigation area also make use of the coupling of an inference engine with a knowledge base. Of course, in the smart sensor area, the system will not have interface -- friendly or otherwise -- with a human; and in both areas, the knowledge bases are considerably more problematical that in the maintenance/test area.

I look forward to meeting with you at the conference in April.

Sincerely,

R. P. Caren

R. P. Caren

RPC:cc

Attachments (2)

ARTIFICIAL INTELLIGENCE APPLICATIONS TO EQUIPMENT MAINTENANCE AND TESTING; ONR INPUT

1. An A.I. Based Expert System

a. Description: A computerized Expert System which provides advice to humans on the trouble shoot, diagnosis, and repair aspects of equipment maintenance. Beyond containing the conventional "if-then rules", this system offers idiosyncration interaction or consulting help to the human in a multiplicity of forms: the user can interact or have advice rendered via speech, printed narrative, graphics, cartoons, motion pictures, or animated drawings/blueprints. To the concern with the burden of completing maintenance forms reflective of the repair, this futuristic system casts up on a portable CRT facimiles of all maintenance forms. The user substitutes a touch-screen input device for pencil annotations; for example, in the case of parts used in the repair, the screen lists all parts (nomenclatures and stock numbers) appropriate to the repair. The user touches the parts he has actually used and indicates, by touching numbers appearing on his screen, whether he has used one, two, three, etc. of each part. The system, then, automatically fetches and prints in the appropriate block such data as unit of issue, unit price, total dollar value of all parts used, manufacturer's drawing number, etc. Additional to advising on standard repairs, the expert system consults on jury-rigs, substitute parts and cannibilization candidates. It also automatically updates all appropriate records, e.g., stock record cards, order levels. The system of the future is highly interactive —— permitting users, via their portable terminals, to input comments on standard procedures or to recommend new repair procedures.

b. Approach

(1) Select example high value equipments; value judged by cost, military essentiality, and/or concerns about excessive downtime.

(2) Establish, via knowledge engineering interview techniques, appropriate production rules (if-then statements) for the candidate equipments.

(3) Explore video-disc technology for the man-machine interaction.

(4) Design portable terminals and test equipments for maintenance personnel.

(5) Build databases.

(6) Develop methodology for dynamic validation of rules.

c. Estimated Time and Costs

(1) Time and costs depend on number of equipments for which expert rules must be developed.

(2) Costs for a required two to three year applied R&D expert; approximately 1M to 1.5M.

d. Impact on Readiness

(1) Advantages

(a) Dramatic improvement in the demonstrated capabilities of maintenance technicians.

(b) Improved quality of repair --- speed up in fault diagnosis and correction.

(c) Reduction in man-power requirements.

(d) Reduction in human skill needs.

e. Technical Risks

(1) It may be difficult to develop a template of production rules slots and procedures that apply over a broad range of equipments.

(2) Costs of acquiring rules for vast numbers of equipments may be prohibitive.

(3) Costs of building the man-machine system (voice, graphics, motion pictures, etc.) tailored to each equipment will be high, and may vary as a function of scale.

2. Automating the Creation and Presentation of Technical Manuals

a. Description: A methodology for generating both color graphics and narrative to the goal of automating the production of technical manuals and instruction books. This same technology, combining pictures, ideographics, and text, permits the digitization and computer storage of technical documents with the capability for real time, remote terminal access of all stored data (text and pictures).

b. Approach

(1) Designate DoD R&D agencies to replicate prototype capabilities now being demonstrated at 6.1 funded university labs.

(2) Conduct experiments to prove feasiblity of a full scale operational/production version of the prototype system.

(3) Create A.I. reasoning capability for labeling, titling, and indexing the graphic images, and for generation and matching text and pictures.

(4) Develop rules for generalizing this capability across designated categories of equipments.

c. Estimated Time and Costs

(1) Three years and 1.5 to 2.0M.

d. Impact on Readiness

(1) Improved quality of technical manuals.

(2) Reduced costs of generating manuals.

(3) Via computerized store of technical documents --- the system both saves space of storing voluminous paper documents and offers real time, remote access to all required maintenance data.

e. Technical Risks

(1) Difficulty of generalizing the capability across equipments.

(2) Developing a methodology for assigning index terms to pictures.

(3) Creating a concept of a thesauries of index terms to permit retrieval by users who are not familiar with the standard terminology.

3. A Natural Language Database Query System in an Equipment Maintenance Context.

a. Description: An English language inquery capability to an equipment maintenance database. This A.I. system could permit on line computerized responses to a large number of factual questions. However, state-of-the-art limitations impose various constraints on the initial implementation of such systems: (1) responses confined to fairly simple factual questions; no treatment of what-if questions, (2) a limited vocabulary or semantic base; primarily a noun and verb world, and (3) avoidance of psychological nuances of languages. Examples of questions answerable by a state-of-the-art natural language system: (1) Provide Federal Stock Number for a given Manufacturer's plan and piece number, (2) How many parts of a designated stock number failed on a particular aircraft type; in a bounded time period; over all aircraft; etc., (3) Dollar value of failed parts.

b. Approach

(1) Designate DoD agency to evaluate state-of-art natural language systems.

(2) Choose a maintenance domain or applications area and build a database.

(3) Establish an experimental environment utilizing human military officers and civil service engineering personnel to test the system.

(4) Select appropriate personal computers/terminals.

(5) Collect data on questions answered routinely by the experimental system and those that are either totally rejected, or where the answers are deemed inappropriate.

(6) Using results of the experimental effort, implement production system with caveats on limitations. Refer problems to the natural language research community.

c. Estimated Time and Costs

(1) Two years and 1M.

d. Impact on Readiness

(1) Permits on-line exploration of many more maintenance issues than are possible without a natural language interface.

(2) Encourages direct interaction with maintenance data by senior managers as well as staffers and computer professionals.

(3) Improves material readiness through immediate responsiveness.

e. Technical Risks

(1) Difficulty of introducing a natural language system to high level managers.

(2) Possibility that what is feasible, using current state-of-art technology, will not be satisfactory for operational practice.

4. Machine Reasoning in an Equipment Maintenance Context

a. Description: A fully automated A.I. reasoning system that offers answers to truly complex questions, e.g., provide an explanation and rationale for an observed series of aircraft crashes or equipment failures. Given the development of an appropriate database (configuration files, failure data, maintenance histories, and personnel files) this advanced machine reasoning system invents its own search strategy to probe for such reasonable possible answers as: (1) all of the planes which crashed shared in common: a missed or extended overhaul; a unique pattern of failures that preceded and anticipated the crash; a unique equipment configuration; all were manufactured consecutively at a given plant.

b. Approach

(1) More support for the basic research A.I. community.

c. Estimated Time and Costs

(1) Five to ten years.

d. Impact on Readiness

(1) Quickly and accurately arrives at explanations of underlying causes of major maintenance disasters.

(2) In lieu of arriving at global answers iteratively and slowly by building systems that provide one by one responses to thousands of simple questions --- this system goes directly and swiftly to the heart of the matter --- provide me, the interrogator, an explanation of what might have caused the crash of those planes.

e. Technical Risks

(1) Reasoning is, perhaps, the most challenging problem that confronts Artificial Intelligence.

5. Computer Driven Crisis Alerting System

a. Description: From the high level logistics command perspective, there is a need to develop "activist" computer systems with capabilities both for recognizing impending crisis situations, and for sounding the appropriate alert or alarm prior to their occurrence. To appreciate the utility of an alerting or triggering mechanism, one has only to reflect on the passive nature of the best available computer systems on the market today. Only to the degree that the right questions are asked by the right person at precisely the right point in time does this passive interactive capability support the decision maker's requirements. An alert capability, in contrast to passive management support systems, is a concept wherein threshold or alarm conditions, initially assigned by knowledgeable commanders, are continually machine monitored and compared with the dynamic, incoming data stream. Alert or alarm thresholds (representing a manager's anticipation of an impending or potential crisis situation) are relatable to almost all of the command and managerial responsibilities of logisitics deployment. Particular examples include: computer monitoring of the behavior of equipments and complex interactions across equipments; machine anticipation and warning of increasing failure rates and the possible shortfall of spare parts; alerting on unanticipated increases in failure rates resulting from the implementation of scheduled maintenance policies; a warning on the impending unavailability or delays in delivery schedules of logistics resources.

b. Approach

(1) Create a database.

(2) Involve a user community in establishing logistics thresholds (alert conditions).

(3) Establish a dynamic database collection effort.

(4) Design algorithms for machine matching of dynamic data stream against thresholds.

(5) Develop (through experimentation) insights on optimal methodologies for calling "alerts" to the attention of logistics commanders, e.g., narrative messages printed at terminals, voice alerts, graphics messages.

(6) Build A.I. capability for system self designation of thresholds.

c. Estimated Time and Costs

(1) Two years and 1M

d. Impact on Readiness

(1) An alerting system would permit anticipation and possible prevention of impending logistics crises.

e. Technical Risks

(1) Capability of logistics commanders to determine and set thresholds.

(2) Building a computational engine that ensures real time pattern matching between machine stored thresholds and incoming dynamic data stream.

Marvin Denicoff

MARVIN DENICOFF

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91109*

February 15, 1983

Mr. Anthony Coppola
RBET/A. Coppola/AV 587-4726
RADC/RBET
315-330-4726
Griffiss AFB, NY 13441

Dear Mr. Coppola:

I cannot participate in the DoD study on AI applications to testing due to the press of other business; however, I can make some brief recommendations which are philosophical in nature, rather than addressed to particulars. My experience is in AI, and my group has been engaged in building two sorts of expert systems. These are: a Planner (used for generating computer code), and a Diagnostician (used for locating faults in electro-mechanical systems). We are at present attempting to integrate the two into a larger system, a feedback loop, that will provide automated command and control with error recovery.

My view is similar to that of Randy Schumacher of ONR. It is his opinion that the next generation of military hardware will be so sophisticated and complex that the present approach of ATE, requiring the test of every possible fault and the pre-construction of fixed fault-diagnosis trees, will inevitably fail in determining faults for the next generation of hardware. I have heard statistics that indicate that even present ATE equipment doesn't work very well. To approach this problem properly requires a basic change in direction. My recommendation is to develop Diagnostic expert systems that approach the problem as a trained human trouble-shooter would, using failure physics and knowledge of how the apparatus to be diagnosed is constructed. That is how our present system is implemented. It also has the advantage of being broadly general-purpose, so that the same diagnostician will diagnose failures in a spacecraft, or the ground system, or robotics problems. Only the knowledge base has to be changed to describe the system under investigation.

a. Recommended DoD action: Fund a research and development program to largely replace ATE systems with expert AI diagnosticians.

b. Suggested approach: Select a competent group or groups willing to undertake this development. Forget ADA, use the LISP language, and LISP machines for hardware.

c. Estimated time and cost: Two years; five to ten man-years to program the expert systems. Preparation of multitudinous data bases would take longer, but would use the same expert systems over and over.

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Mr. Anthony Coppola February 15, 1983

<u>Impact</u>

Advantages: Would diagnose all the faults quickly diagnosed by a human and could also do the most common difficult diagnoses. Would attack the most common problems that arise rather than every conceivable problem. Would cost far less to implement than present ATE systems and would work better.

Disadvantages: Would require the junking of many existing AF systems in which there are large investments.

Sincerely,

Leonard Friedman, Bldg. 278
Automated Problem-Solving
Group Supervisor

LF:mb

TO: MAJOR PHILIP CORM
c/o AFSC/DLZ (DR. KULP)

Attached is an edited copy of Russ Genet's input to Bob Sasmor for the Training and Simulation (include Maintenance Performance) Work Group of the JDL/TIP for AI. Although the AFHRL/LR Division Chief and I have read and edited, this is submitted outside official channels and has not been submitted for the usual staff reviews or approval by AFHRL/CC.

EARL A. ALLUISI
AFHRL/CCN

ARTIFICIAL INTELLIGENCE IN MAINTENANCE AND DIAGNOSTICS

Russell M. Genet
Logistics and Human Factors Division
Air Force Human Resources Laboratory

INTRODUCTION

In planning its research and development (R&D) programs, the Air Force Human Resources Laboratory (AFHRL) must consider the direction and impact of technology on the future conduct of Air Force operations, as many years usually pass between laboratory R&D efforts and applications of the R&D findings in the operational Air Force. Thus, it is imperative that the laboratories conduct R&D in areas that are appropriate to the technology expected to be fielded a decade or more in the future. In considering what R&D is appropriate for the Logistics and Human Factors Division of AFHRL, thought needs to be given to the nature of logistical support in the Air Force of the future. In this brief paper, the area of equipment maintenance is addressed — particularly, the area of diagnostics of equipment faults at the field level.

What trends can be seen in Air Force equipment and its diagnosis that would be helpful in predicting what this area will look like 10 or 20 years from now? There is a trend towards increased use of electronics rather than mechanical equipment. A good example of this is fuel control systems on jet engines, and another is flight controls. There is also a trend away from analog electronics towards all or almost all digital systems. Equipments are increasingly using embedded microcomputers and "speaking" to other equipments over standardized busses. Equipments on aircraft and missiles are communicating more often with ground equipments via digital communication channels. Increasing use is being made of built-in-test-equipment (BITE). As the amount of BITE (including in-flight monitoring) increases, it will doubtlessly be standardized and consolidated over entire aircraft and other weapon systems. These various improvements should enhance diagnostic decisionmaking and hence substantially reduce the currently high rates of "retest OKs" and "cannot duplicates" (CNDs).

Already, a similar, and perhaps more extensive revolution is taking place in the ways data are handled, accessed, and decisions made. It is clear that in the future, large amounts of technical data will be accessed by Air Force technicians via interactive computers. The technology to store, retrieve, and transmit vast amounts of data digitally via computers is here today. The printed technical order (TO) as we know it today will become an anachronism in the future. In the future TOs will be produced and accessed via computers. However, these computerized TOs of the future will not be TOs as we know them today; the Air Force maintenance technician will be able to react and converse with this computerized system. Also, the system will be able to learn and adjust its behavior.

In short, we can expect that in the Air Force of the future we will be mainly dealing with complex digital electronic systems in our maintenance tasks, and that we will use "smart" digital computers to assist us in our maintenance and diagnostics tasks. This is, technically, an application of Artificial Intelligence (AI).

Just as we can expect the BITE electronics on the various avionics and propulsion systems to become an integrated whole (and it would be silly for future aircraft to have a bunch of separate BITE systems), similarly we can expect the maintenance information systems to become integrated. It would not be practicable to have one system to provide TO-type information, another to give suggestions on what technicians might consider next in their diagnostics (an AI-based diagnostics system), another to record maintenance actions, and even another to order replacement items from supply, etc. It will be imperative that there be a single integrated maintenance information system. I know a number of local supermarkets that have been able to integrate their pricing, inventory, ordering, etc., into a single computerized information system. It seems likely that the Air Force will see the advantage of such integration also.

The combination of (1) consolidated and continuously monitoring BITE systems, (2) computerized and interactive use of technical and maintenance data, and (3) applications of these techniques along with artificial intelligence (AI) should substantially improve maintenance in the Air Force of the future. It might be well to keep in mind that the application of AI to improve maintenance diagnostics, and hence readiness and sortie rates, is not likely to be overlooked by other Air Forces. In an editorial in the January 7, 1983 issue of Science, Philip H. Abelson points out that "One area in which the Japanese seem particularly eager to excel is artificial intelligence." Professor Edward Feigenbaum of Stanford believes that we are at the beginning of a second computer revolution and that ultimately applications of artificial intelligence will become more important that numbercrunching. Calling to mind Pearl Harbor he said, "At dawn we slept."

ARTIFICIAL INTELLIGENCE IN MEDICINE (AIM)

Presuming that future Air Force maintenance information and diagnostics systems will be aided by computerized artificial intelligence (AI) systems, are there any such systems currently, even in other areas, from which Air Force researchers might be able to learn? The answer is, of course, yes that

AI has been applied already to medical diagnostics. In a very small task for AFHRL, Dr. Ben Schwartz took an unbiased look at AI in Medicine and Public Health, and its relation to future Air Force maintenance information and diagnostics systems.

Four artificial intelligence in medicine (AIM) projects emerged from his literature search and interviews. Two of them appear to be, if not more important, at least more widely known than the others. They are MYCIN, an AIM program developed at Stanford Medical Center; and INTERNIST, a product of the New England General Hospital in Boston.

MYCIN is a knowledge-based (expert) consulting system to assist in selection of medication (specifically antibiotics) for infections and meningitis. MYCIN is primarily a therapeutic consultant - the diagnosis is assumed already accomplished and is not part of the AI function. The decision of an anti-bacterial agent is complicated. It involves the infecting agent and its susceptability to specific medication; site of infection; route of introduction of medication; patient weight, metabolism, and condition (e.g. immuno suppression medication, trauma); contraindications (allergy, drug interactions); and several other features. Each factor is easy to deal with individually, but the combination of all is often beyond the mental capabilities of the human health-care provider. MYCIN serves as a consultant, making recommendations or responding to suggestions of the providers. It is capable of interaction with the provider. For example, it is able to respond to the query "WHY DO YOU SUGGEST THAT?" (this feature was highly valued by users in several tests).

Both users and outside evaluators in double blind tests have given MYCIN high ratings as an adjunct (never a substitute) for the human health-care provider.

INTERNIST is a diagnostic, rather than therapeutic AIM system. It also is considered a knowledge-based (expert) consulting system.

INTERNIST begins with a symptom and condition report supplied by the physician in basically unstructured form. It matches information items against a variety of disease conditions for strength of association. It then returns to the user to request additional information in a sequence calculated to be most effective in reducing the possibilities. Like MYCIN, it will function interactively.

INTERNIST was rated as a "diagnostician" in tests. It scored better than medical students, slightly worse than practicing nonspecialist physicians, and substantially worse than specialists. However, it was not designed to be a stand-alone system but rather a member of the man-machine team. Users consistently report that the system enhances their diagnostic talents.

The rapidly growing R&D and applications gives credence to the claim that AIM is a topic of considerable current interest and activity, particularly with respect to diagnosis. A provocative question to ask is: Can concepts and techniques developed in the context of AIM be transferred to the manmade but inanimate system (electronic, mechanical, etc.) maintenance problem environment? Clear analogies can be drawn between medical diagnosis and fault diagnosis for inanimate systems. Both human systems and inanimate systems deteriorate over time, are coherent (i.e. comprised of interacting multiple components), and can be thought of as fault tolerant in many problem contexts. The analogy, however, is not perfect. A human can make transition into an improved state of health, whereas spontaneous transition into an improve system state for an inanimate system is highly improbable, if not impossible.

The AIM systems considered by Ben Schwartz were all expert-based systems. As such, they can capture the wisdom of the experienced "master sergeants" and make this experience available to the new recruit. However, experts could have cognitive and behavioral biases that may intrinsically prohibit them from determining optimal or good suboptimal maintenance procedures for large-scale maintenance problems, and an expert system could propagate such biases. It seems likely, however, that eventually AI systems will be able to blend the best of the expert master sergeant's wisdom with an accumulating data base of actual maintenance decisions and outcomes in a manner that will allow the AI maintenance system to get smarter over time. For this to occur, it will be necessary, of course, that maintenance data routinely be captured by the system. This suggests, again, the close ties between an integrated maintenance information system, the consolidated avionics/propulsion/etc., BITE that feeds the integrated maintenance information system, and the AI system that serves as the interface between the computerized systems and the maintenance technicians, and also serves as the repository of the accumulated expertise of the "super stripers".

ARTIFICIAL INTELLIGENCE IN EQUIPMENT MAINTENANCE

While the medical AI systems have obvious applicability to the maintenance of Air Force equipment, has AI been applied directly to the problem of equipment maintenance? Surprisingly, the answer is a definite "yes". The AI researchers at Stanford that developed MYCIN realized that their expert-based approach had many applications beyond the medical field. To facilitate the AI expert systems approach in other areas, they generalized MYCIN into an AI system known as EMYCIN that provided the computerized framework for the development of any computerized AI expert system, and also serves as a basis and repository for capturing the necessary expert information.

In an in-house R&D effort, the Boeing Company has taken EMYCIN and applied it to an equipment maintenance task. The equipment they chose for this pioneering demonstration was a Hewlett Packard printer, as it contained both electronic and mechanical components, and there were experts on the maintenance of this system available so that the AI knowledge base could be built. The first phase of this in-house project has been successfully completed, and the capabilities of an AI expert system to aid in equipment maintenance has been demonstrated. The next step is probably the demonstration of the use of an AI expert system in the maintenance of Air Force equipment under realistic military conditions.

AIR FORCE AI R&D DEFINITION EFFORTS

There are three closely related and supportive efforts underway in the Air Force to identify what AI R&D should be undertaken with respect to maintenance, testability, and training. The first is a $100K task from AFHRL/LR to Systems Exploration on "Artificial Intelligence in Maintenance Diagnostics and Information Systems". The objective of this task, which has just started, is to identify potential AI research directions and projects with good payoff prospects. Such projects would be expected to result in improved human performance of avionic maintenance tasks. The second, and closely related and coordinated task is from AFHRL/TU, and is being accomplished by the University of Denver Research Institute on training applications of AI in the Air Force. Particular attention is being paid to technical training as it relates to the maintenance of electronic equipment. A one-year, $150K study is about to be awarded from RADC. This study will survey existing and developing AI techniques for applications to testability — particularly built-in-test-equipment (BITE). Emphasis is being placed on those AI techniques capable of practical application to testability programs in the very near future.

A COORDINATED TECHNOLOGY-BASE DEMONSTRATION PROGRAM

As suggested earlier, for an AI-based maintenance/diagnostics system to work at all, it needs to be provided with information from a consolidated aircraft/system-wide BITE system, and an integrated maintenance information system. The consolidated BITE, integrated maintenance information system, and AI expert system form an interacting triad that supports the maintenance technician in efficiently and quickly accomplishing his duties. All three of these elements require development in a 6.2 program with initial demonstration in a 6.3 program. While these three elements of the triad must be developed together in closely coordinated programs, it would be useful to consider them individually just for the purpose of clarifying the individual pieces.

A 6.2 AI DEMONSTRATION PROGRAM

A demonstration of AI on the maintenance of a selected Air Force electronic digital system will be the objective of this program. The approach taken will be a combined rule-based (expert) and causal technology. The latter portion of the technology takes advantage of the fact that there are many built-in logical relationships in equipments. The first 18 months and $600K of the two part program will be to verify that this technology will work. The second part of the program would demonstrate this capability on a specific piece of Air Force equipment. The second part would take an additional 12 months and $900K.

A 6.2 INTEGRATED MAINTENANCE INFORMATION SYSTEM DEMONSTRATION

The Integrated Maintenance Information System (IMIS), is a proposal for providing all necessary automation to flightline personnel in one compact, user friendly device. IMIS would provide the interface between the maintenance technician and the AI expert diagnostic system. However, IMIS would go beyond diagnostics and also provide the technician with technical order information, training, supply information, aircraft schedules, aircraft history, and maintenance record keeping. The first 12 month part of this exploratory development program would define in considerable detail the maintenance information that needed to be integrated and define the data base requirements for the integrated system. This phase would cost $1.9M. The second phase would involve developing a prototype IMIS system. This phase would take 18 months and cost $3.6M. In the third phase the prototype would be extensively evaluated in a field environment over a period of 10 months ($1.6M).

A 6.2 INTEGRATED DIAGNOSTICS PROGRAM

The Air Force philosophy for future maintenance is that every fielded weapon system will have a 100% diagnostic capability. This capability should be provided by trained people and automated systems in the the most effective combination. In addition, future fighter aircraft will need to be maintained and turned for a combat sortie in a minimum of fifteen minutes. This will have to be accomplished with a minimal number of people who are not extensively trained nor experienced over the entire range of possible malfunctions.

To achieve these future maintenance goals, this exploratory development effort will partition which tasks will be automated and which tasks are best suited to the maintenance technician for diagnostic maintenance purposes. In addition, it will determine what information is required and how it can most effectively be presented. It will also insure that redundancy exists to compensate for deficiencies in the equipment of the maintenance technician (100% diagnostics). This research effort will consist of two major phases. The first phase will provide a method to quantify what information can be automated and what should be taught. This will be weighed against operational requirements to insure a proper mix of combat maintenance capability. The estimated cost is three years and $2M. The second phase will be to design and field test a system with technician support to prove the 100% diagnostic maintenance philosophy. This will take two years and $1.2M.

A COMPREHENSIVE 6.3 DEMOSTRATION PROGRAM

Once the basic technical feasibility had been established in the exploratory development program, it would be necessary to demonstrate in a realistic Air Force environment that the concepts would work out in practice. Ideally this should be done on some newly developed aircraft system as a test bed. The development of the consolidated BITE, integrated maintenance information system, and AI expert system for such a demonstration is estimated to take three years.

SUMMARY

The use of AI in a consolidated maintenance information and diagnostics system for the support of Air Force equipment is not a "far out" project, but it is almost certain to be the basis of maintenance in one or two decades. Thus, it behooves the Air Force to start research in this area as quickly as possible. That such an application of AI is practicable has been suggested by its application in medicine and by the pioneering research at Boeing. It is particularly pertinent that AFHRL be involved in this research effort, as it is at the forefront of man/machine interfacing and interaction, and it is in the area of logistics resources. AI expert systems take their knowledge from humans and interact with humans. It seems likely that this blending of human and computer resources will be an increasing topic for research at AFHRL.

ARTIFICIAL INTELLIGENCE APPLICATIONS TO TESTING

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POSITION STATEMENT

All military services are confronted with increased training costs, reduced training budgets and a widening gap between the skills of entry-level personnel and the abilities required to maintain increasingly sophisticated systems. Institutional training is minimized, and more emphasis is placed on on-the-job training. This requires a greater reliance on built-in test equipment and organic automatic test equipment support. Unfortunately, automated testing (built-in or off-line) does not unambiguously fault isolate all of the time. The result is a high rate (up to 30%) of removal and replacement of non-faulty assemblies. Reduction of the number of suspected faulty assemblies within an ambiquity group requires manual troubleshooting. The manual troubleshooting procedure used to fault isolate to a single assembly typically involves a brute-force and exhaustive method of remove-replace-retest. This manual troubleshooting method is expensive in terms of both test time and logistical support. Our premise is that a solution lies in improving on-the-job training and job performance aids. We need to provide tools at the job-site that will enable maintenance personnel to pick up where automated diagnostics leave off; thus fault isolation and repair can be completed in a direct and efficient manner. Our approach combines enhanced job performance aiding and on-the-job training by means of a computer-based intelligent advisor, or troubleshooting coach. The advisor embodies the knowledge of an expert maintenance technician and aids in fault diagnosis and fault isolation. The advisor also acts as teacher, having the capability to explain recommended actions and lines of reasoning.

In recent years, knowledge-based systems and system-building tools developed by researchers in artificial intelligence have been exposed to the general public. The success of programs that perform medical diagnosis (MYCIN, INTERNIST), develop a VAX computer configuration based on customer requirements (R1 or XCON), or locate mineral deposits (PROSPECTOR), offers promise for other applications where expert practitioners are in short supply. One of those applications is the diagnosis and isolation of faults in electronic equipment.

RECOMMENDED DOD ACTION

A focused effort is required to develop system-building tools for knowledge-based (expert) maintenance aids. The software tools would be used to develop application packages for training and aiding maintenance technicians at the job site.

SUGGESTED APPROACH

The unique architecture of most knowledge-based systems, i.e., the distinct separation of the knowledge base (a set of declarative and procedural rules) from the inference procedure, makes them extensible, capable of handling inexact inference and gives them the ability to explain lines of reasoning. Of the current system-building tools that may be applicable to equipment maintenance, all require the services of a knowledge engineer to act as go-between to formulate the knowledge of a subject matter expert into expressions that can be used by the inference mechanism of the system. This so-called knowledge engineering bottleneck is costly, time consuming and severely limits the number of potential applications. We need a means by which the expert maintainer (the domain expert) can directly create and modify an application knowledge base. But we must do more than that. The knowledge of a domain is based on structure (in our case, how equipment is put togther) and function (how the equipment works). We should not have to burden the expert maintainer with the task of defining the declarative and procedural rules related to structure. The software tools that help to automate the knowledge acquisition process must include friendly interfaces, both for the expert maintainer who participates in development of an application package, as well as for the maintenance technician. The software must be self-tutoring to obviate specialized training and must possess a supportive query mechanism.

For widest use, the system-building tools should be designed to support training and aiding at all levels of repair. The final product should be available in Ada for portability. Prime item specifications should require the documentation necessary to support application package development.

ESTIMATED TIME TO COMPLETION AND COST

The time required to develop a complete and supportable product is estimated to be five years. We expect that the development process would be iterative, with a prototype available for evaluation after the first eighteen months of the project. The staffing is estimated at an average of ten professionals each year. The computing resources (workstations, other computer time) required to support this effort are estimated at $1M over the five year period. Adding labor costs (e.g., $0.8M each year), the five year project cost would be approximately $5M.

IMPACT ON OPERATIONAL READINESS

If aircraft subsystems are down, the aircraft are down. Under mobilization, brute-force maintenance procedures would be neither supportable nor acceptable. Improved training and aiding at the job site will result in more efficient maintenance actions, with less reliance on logistics support.

TECHNOLOGICAL RISK

Currently, there are several knowledge-based systems performing useful tasks on a regular basis. We know that the techniques developed so far work well for specific narrow domains in which the expert knowledge is neatly bounded. The depth and breadth of success of these techniques when applied to electronics maintenance will not be known until we try them on a representative set of real-world problems.

GENERAL COMMENTS

University research centers are not recommended as lead organizations for this work. The development recommended here should be directed and performed by maintenance practitioners having first-hand knowledge of DoD readiness problems. Support will, of course, be required from artificial intelligence specialists; however, the emphasis must be on application rather than research.

POSITION PAPER

ARTIFICIAL INTELLIGENCE APPLICATIONS

TO MAINTENANCE AND TESTING

By Robert Hong

The DoD has made a long-term commitment to enhance the availability of defense weapon systems in both peace and wartime environments and to do so as economically as possible. The objective of this study is to identify opportunities for improving readiness of military systems by means of artificial intelligence (AI) techniques. The emphasis is to be on its applications to maintenance and testing. The results are intended for possible application as appropriate, to new weapons systems and subsystems now in the planning or development stage.

Most of the recent successes in AI are in knowledge based systems (KBS) or expert systems. Some theorem proving approaches such as automated reasoning have also performed as well or better than human experts. In the past few years, a number of papers have been published on the subject of AI applications to maintenance and testing. In general, they are on the right track and I will not repeat them here.

The time frame for developing the AI systems DoD might place into operation is important. Probably the earliest these new systems will be operational will be 3-5 years from go-ahead. By that time, for various reasons such as the Fifth Generation Computer Project and the VHSIC Program, AI technology advancement will have accelerated significantly and available computational power will be several orders of magnitude greater than now. In addition, several NON-VON type AI processors might be available that will overcome some of limitation in applying AI to (near) real-time problems. Many LISP type machines are available now.

AI, especially KBS, can be applied to a wide range of areas to improve readiness and availability of weapon systems. In addition to maintenance and testing, AI can be used for CAI and optimizing logistics. Before we get specific regarding particular applications, several areas needs to be addressed. Some of these are as follows:

- The standard programming language to be adopted.
- The computer/processor systems to standardized on. (Will there be a standard?)
- The KBS now in development belong to the second generation. The relatively simple organization of such first generation KBS as MYCIN is probably not efficient for many of the applications of concern here.
- The number of man hours required to develop KBS till now are quite large. Various tools are being developed to minimize the cost of KBS. More are needed.
- Techniques are needed to make KBS more user-friendly.
- There is some concern regarding the adequacy of shallow reasoning to handle more complex problems.

The language to be adopted may be one of the AI languages such as LISP or PROLOG. Experience has shown that PROLOG is very much easier to learn than LISP. However, there are other tradeoffs. The use of such standard language as ADA would require additional instructions in its repertoire.

What computers are to be considered? Several parallel processors for AI are being developed. The use of associative memory and processors have been evaluated for this purpose by Grumman and others.

An examination of the internal organization of the first generation KBS show that the sophistication of their capacity to represent most of what they deal with is extremely limited. Almost universally, important notions such as the relations between hypotheses, degree of beliefs, models, temporal relationships, diagnostics, plans, etc., are either missing altogether or else represented by very simple medianisms that miss much of the subtlety of human reasoning. The second generation KBS as a minimum are developing new representational techniques to overcome these limitations.

Various tools such as that for the difficult task of knowledge acquisition have been developed. Several automated programming systems are being developed. These range from programming assistants (apprentice), to knowledge programmers, and finally to fully automated systems. These should allow the domain expert to provide knowledge directly to the expert system without the need of an AI expert. The result should be a much lower development cost.

As KBS are being applied to more sophisticated problems, there will most probably be a need to incorporate deep reasoning capability to complement shallow reasoning. This would include aspects such as causality, physical (first) principles, theorem proving, and non-monotonic reasoning.

In addition to automated knowledge acquisition and automated programming, improved man-machine interface with KBS should be steps to making the kBS more user-friendly.

With the above as a basis, the following are the specific recommendations:

1. a) Recommended DoD action

   Design ATG for at least two level of complexity in fault diagnosis. One for routine cases and the other for more challenging failures. It will also have self improvement and possibly some learning capabilities. This will be for digital systems.

b) Suggested approach

Use shallow reasoning for routine cases. For the more challenging failures, use shallow and deep reasoning. Grumman LOGOS / DATPG to form basis for this work.

c) Estimated time to completion and cost (dollars or man-years)

For a demonstration system, and assuming availability of tools. 2 years, $200,000 computer costs and 6 man years of effort.

d) Impact on operational readiness

(1) Advantages - significant reduction in number and skill level of personnel. Improve testability.

(2) Disadvantage - requires more computer through put and memory.

2. a) Apply KBS to design of VLSI with BIT and testability directly on each chip.

b) Use recently developed expert assistant for VLSI design by Mark Stefik and Lynn Conway of Xerox PARC. Then develop equivalent (hierarchical) KBS BIT with capability for testability on each chip.

c) For one type (microprocessor) demonstration VLSI, 1 yr.: $100,000 computer costs, and 3 man years of effort.

d) (1) Advantage - significant reduction in development man-hours. Provide building blocks of fully testable chips for airborne and ATE equip. thus improve readiness.

(2) Disadvantage - insignifcant.

3. a) Develop KBS to diagnose jet engine failures.

b) Apply both shallow and deep reasoning approaches. Use applicable techniques developed for nuclear plant fault prediction and prevention.

c) 2 yrs.: $200,000 computer costs and 12 man years of effort.

d) (1) Advantages - Capability to predicting and prevent failures. Ability to structure maintenance to the actual needs of the operating equipment thus reducing maintenance manhours.

(2) Disadvantages - Requires more processing capability and memory.

4. a) Develop KBS for situation assessment/resource allocation for spares.

   b) Apply multi-membership hierarchical type KBS emphasizing knowledge representation and elicitation.

   c) 2 yrs.: $200,000 computer costs and 6 man years of effort.

   d) (1) Advantage - Reduces support tail (reduce parts count, improve efficiency)

      (2) Disadvantage - Requires use of powerful computer.

5. a) Develop KBS CAI to provide training for ATE users.

   b) Use video game approach and teach personnel the latest learning techniques suggested by cognitive psychologists (e.g. from CMU).

   c) 2 yrs.: $200,000 computer costs and 6 man years of effort.

   d) (1) Advantages - Significant improvement in skill level and motivation to support personnel. Reduce requirement for instructors.

      (2) Disadvantage - Additional CAI equipment.

6. a) Develop parallel computer/processor for KBS in military applications.

   b) Take advantage of associative memory/processing. Use CAD (e.g. SCALD).

   c) 2 yrs.: $200,000 computer costs and 6 man years of effort. $3M for hardware.

   d) (1) Advantages - Significantly greater processing capability for KBS.

      (2) Disadvantage - Additional processor.

7. a) Develop ATG KBS for fault diagnosis of analog circuits.

   b) Evaluate the applicability of signal-to-symbol transformation, especially for RF. See Footnote Page 5.

   c) 2 yrs.: $200,000 computer costs and 6 man years of effort.

   d) (1) Advantages - Significant reduction in processing requirement.

      (2) Disadvantage - Insignificant.

8. a) Automate the total life cycle KBS software effort. Develop KBS workstation.

b) Take advantage of work in progress at Kestral Institute, MIT, Rand Corp., Schlumberger, ISI, etc.

c) 2 yrs.: $400,000 computer costs and 24 man years of effort.

d) (1) Advantages - Minimize one of the major cost elements in KBS.

(2) Disadvantage - Major undertaking.

9. a) Develop KBS techniques for in-flight perform monitor / on-board checkout system for both avionics and non-avionics which could also be part of graceful degradation and self-organizing system. Reduce false alarm rate.

b) Use both shallow and deep reasoning techniques.

c) 2 yrs.: $200,000 computer cost and 6 man years of effort.

d) (1) Advantages - Improve mission success and reduce false alarm rate. Improve flight safety as a result of monitoring overstress conditions, etc.

(2) Disadvantage - More processing and memory required.

Footnote

AI search techniques will be employed on graph theoretic circuit representations in order to optimize test point selection and enhance testability (adaptively, if necessary).

Thereafter, data driven algorithmic formulations based on modern circuit theory will actually locate failure sources.

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