An Airborne Manual/Automatic Malfunction Detection System

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The C-5A system was designed to detect malfunctions to the line-replaceable-unit (LRU) level on selected aircraft systems. Although the depth of monitoring varies among these systems, the detection scheme has been applied to the electrical, electronic, environmental, mechanical, and propulsion systems. Signal monitoring units are located throughout the aircraft and multiplexed information is routed to either the manual or automatic mode for evaluation. Manual-mode evaluation is accomplished by an operator using projected information whereas a digital computer is utilized for the automatic-mode evaluation. The system is comprised of 40 components; however, 31 of these are nearly-identical signal monitoring units. Approximately 800 test points have been selected by thorough fault analyses of the monitored systems. Many LRU's can be investigated without actual interconnection, by using displayed test procedures. Extensive simulator and flight tests have been planned to verify signal levels, detection routines, and computer program.

Introduction

Air Force direction for the C-5 proposal required a maintenance system capable of providing maximum reliability, accuracy, speed, flexibility, and simplicity. Further, the system had, as a design goal, the requirement for testing down to the lowest line replaceable unit (LRU) and a subsequent announcement to the crew as well as a record-keeping entry. Previous experience had indicated that a manned maintenance system offered more potential capability than a completely automatic and unmanned system. Since the C-5 crew complement did not include a person whose prime purpose was maintenance, Lockheed investigated the incorporation of the maintenance function into the duties of a crew member. The logical choice was the flight engineer, and the next step was to estimate the time that could be spent performing the maintenance role. A human engineering task analysis indicated that, during normal cruise conditions, approximately 50% of his time could be allocated for maintenance actions. A subsequent human engineering study was devoted to integrating the maintenance control function into the flight engineer's panel.

The synopsis of this direction and experience was to provide a system capable of either identifying a failed LRU immediately upon failure, or predicting the occurrence of a failure. The results of such a system would, therefore, improve turn around time, reduce spares requirements, eliminate specific aerospace ground equipment (AGE) items, and decrease maintenance training requirements. Lockheed investigated the broad spectrum of maintenance techniques presently employed. In general, these techniques are as shown in Table 1 in the order of the complexity.

The first technique uses the normal aircraft controls and indications to detect malfunctioning LRU's. An example of this technique would be the detection of a faulty fuel pump by rerouting manifold flow paths and observing pressure indications. The efficiency of this scheme, however, is directly proportional to the ability of the operator, and is determined by training level, experience, and motivation.

The remaining techniques require onboard hardware in varying degrees of complexity. For ground data reduction, the flight hardware can be relatively simple, whereas the onboard reduction scheme requires computation ability. BITE techniques require operator initiation and temporarily interrupt the normal operation of the monitored system in most cases. Automatic self-test is performed on a noninterference basis and does not alter the monitored system performance.

The announcement of detected failures is usually dependent upon the complexity of the system. Large systems could contain decision-making circuitry, whereas simpler systems may output sufficient logic signals to permit decisions by auxiliary equipment.

After reviewing the directions, goals, and techniques available, the following specific design criteria were established to permit system conception:

1) Malfunction detection to LRU level.
2) Continuous monitoring, noninterference with normal system operation.
3) Announcement of failed LRU identity to operator.
4) Flexibility for addition/deletion of monitored test points.
5) Recording of data for trend analysis.
6) Use of existing sensors where possible.
7) Visual memory of subsystem status by annunciator panel.
8) No addition of stimuli generation.
9) Minimum operator training.
10) Possible use for both ground and inflight tests.

The resulting system took the concept shown in Fig. 1, and exploited the advantages of the malfunction techniques previously mentioned, permitting each to contribute in the areas

Table 1 Malfunction detection techniques

Technique	Announcement
1) Functional manipulation, use of existing instruments	Operator decision
2) Examination of LRU test signals	
a) Ground data reduction	Recording medium processed to determine faulty LRU
b) Onboard data reduction	Signals conditioned, logic levels derived/processed, LRU equations solved
3) Built-in test equipment (BITE)	Operator initiated, functional loop tests
4) Automatic self-test	
a) With summary logic	Monitored system provides logic levels for decoding
b) With internal decision	Monitored system provides failed LRU identification

Presented as Paper 68-269 at the AIAA 2nd Flight Test, Simulation and Support Conference, Los Angeles, Calif., March 25–27, 1968; submitted March 22, 1968.

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in which they perform in the most efficient manner. Lockheed identified the system as the C-5A malfunction detection, analysis and recording system. The acronym "MADAR" was quickly adopted and will be used henceforth in this paper.

As indicated in Fig. 1, the system consists essentially of two subsystems, automatic and manual, which share the printout unit and maintenance data recorder for record keeping. The automatic portion operates whenever the switch is "on." The manual portion, however, is used at the discretion of the operator.

The automatic-mode monitors LRU's that have signal data outputs amenable to digital techniques. Data sampling, value comparison, limit detection, and malfunction printout are performed automatically according to a preprogrammed scheme.

During manual-mode operation, the automatic mode is uninterrupted. The operator uses the manual (or diagnostic) mode whenever he has any reason to suspect a malfunctioning monitored system. For example, a problem may be indicated in the heading loop. The operator will depress the avionics subsystem entry button and a slide will be projected onto the view screen, which will give instructions for initiating an analysis of the heading loop. Specific test points will be called up by a film program, for waveform display and comparison. As the live waveforms are projected, an analysis slide is simultaneously projected, showing typical wave patterns which apply specifically to the selected data point in the loop, with instructions for the next test point. The operator can progress sequentially through the entire heading loop examining the loop for faulty signal data flow and locating any faulty LRU that may appear. The control panel also permits call-up of diagnostic procedures as well as waveforms and test point information.

Technical Description of System

The block diagram (Fig. 1) indicates the components utilized individually and jointly by the automatic and manual modes. The central multiplexer adapter (CMA) serves as the principal interface component. The flow of data into the system is as follows: the signal acquisition remote (SAR) units monitor 30 test points each, and are located throughout the aircraft at optimum locations for minimum wire lengths. The analog signals entering the SAR are normalized and transmitted to either the CMA or the manual multiplexer (MMUX) depending upon signal type. Those signals entering the CMA are digitized and sent to the digital computer (DCOMP) for either malfunction analysis or trend analysis. Out-of-limit signals provided to the DCOMP cause the computer to transmit failed LRU information to the printout unit and maintenance data recorder. The MMUX signals are routed to the control/display (C/D) group for display on the oscilloscope. Operator decisions that indicate malfunctions cause the C/D group to transmit failed LRU information to the print-out unit (POU) and maintenance data recorder (MDR).

Automatic Mode

The system can sequentially monitor up to 960 data points in the automatic mode. If a failure is detected, the LRU number, time of day, and date are automatically printed out in alphanumeric code, and also recorded on the MDR. The subsystem name is illuminated on the C/D subsystem status panel.

The heart of the automatic mode is the digital computer. The computer program selects the test point to be addressed. The SAR, upon receipt of test-point address from the computer via the CMA, selects the proper data gate and routes the data signal from the conditioning circuitry, through the selected gate, to the data amplifier for transmission to the CMA. The signal is then converted to a digital word. For

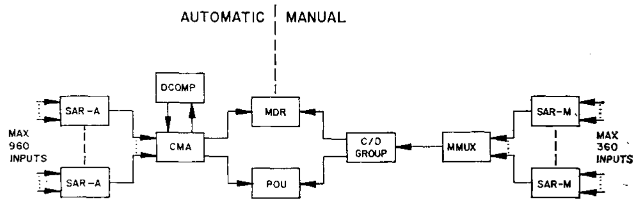

Fig. 1 MADAR block diagram.

automatic-mode signals called up for display by the manual mode, the signal is obtained in the CMA prior to analog-to-digital conversion.

The digital word in the CMA is considered by the computer to be either trend data or LRU data depending upon the program. If the word is trend data, the computer tests the value to determine if it has changed more than its preprogrammed, allowable deviation since its last recorded value. If the value is within the allowable deviation, however, the number, value, and a time reference are supplied to the MDR via the CMA.

LRU data values are tested to determine if they are within a programmed tolerance range. If they are within range, the test data is in a "Go" condition. A value outside this range results in a "No Go" condition. Upon obtaining this condition, all test data points related to the monitored LRU are examined and assigned a "Go" or "No Go" condition. Then a logic equation is formed with the "Go" and "No Go" determinations. This equation is then compared with a known equation of the LRU in a known condition. If the formed LRU equation agrees, then the LRU is good. If the formed equation does not agree, then the LRU has failed. If the status of an LRU changes from the previous status, an output is required. An LRU status change would be defined as an LRU changing from normal operation to a failed condition, or from a failed condition to normal operation. The information output goes to both the MDR and the printout (POU) units.

The arithmetic and branching capabilities of the computer make possible other means of examining data. A transfer function, for example, may be formed from two test points and used in both LRU status determination and trend analysis. The computer can also address the SAR calibrate signals, when SAR calibration is required.

Manual Mode

In the manual mode, the MADAR system provides the operator with a visual waveform display for use in analyzing analog parameters which are not amenable to automatic techniques. Manual operation of the MADAR subsystem is also referred to as the diagnostic mode. Critical analog parameters are analyzed by comparison of simultaneously projected live waveforms and stored film patterns on a cathode-ray oscilloscope and a view screen, respectively.

The manual mode uses the manual SAR's, a MMUX unit, a C/D group, a human operator, and the two output devices, POU and MDR. Each manual SAR functions as two separate remote multiplexers having 15 channels each.

The manual-mode operation is completely controlled by the C/D group. The operator of the C/D Group is the comparator and the decision-making "component" of the manual mode. The operator is also the instigator of the sequence of operation.

LRU status determination by the manual mode is similar to the method used for the automatic mode. The operator selects the desired subsystem and begins the filmed preprogrammed interrogation of the subsystem test points. As each live waveform appears on the oscilloscope, a corresponding film frame is displayed onto the projection screen of the data retrieval unit.

This film frame provides either information or waveforms to the operator in a manner that permits him a "choice" to per-

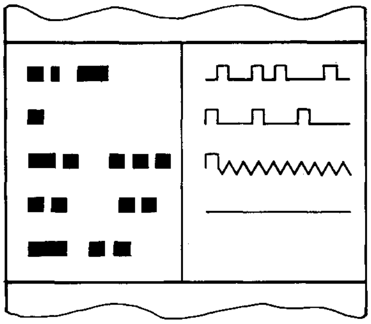

Fig. 2 Film frame format.

mit continued operation. As choices are made, the operator progresses through the programmed diagnosis of the selected subsystem. When an operator's choice reveals an improper waveform, and subsequent faulty LRU, the actuation of the choice switch produces an output to the POU and MDR. The output will include LRU number, subsystem identification, and time.

Random access to any test point is obtained by entering the test point address through the C/D keyboard. The test data signal is thus displayed without regard to any diagnostic subroutine. This operation would probably be performed more often by an experienced technician doing detailed trouble shooting.

There will be approximately 10,000 individual 16-mm film frames. An example of a typical film frame format is shown on Fig. 2. The digital data appears on the left and the information to be displayed on the screen is shown on the right. A single light source is used for projection. The digital data, however, is split off and projected onto a diode matrix bank for decoding. The various digital codes represent choices, addresses, and control settings for the oscilloscope and digital readout unit. The complete programming of the oscilloscope and digital readout unit by film frame data permits its utilization by persons not generally familiar with test equipment. The visual information data provides typical waveforms for operator comparison. Other film frames will provide diagnostic routines, detailed LRU information, and information pertinent to aircraft maintenance.

Component Descriptions

C/D Group

The C/D group is located at the flight engineer's station and provides centralized control of the MADAR system. It is comprized of the oscilloscope and the digital readout unit (ODRU), the data retrieval unit (DRU), and the control and sequencer unit (C/SU), the functions of which are shown below.

1) The control and sequencer unit contains the digital logic necessary to control the operation of the ODRU, DRU, and the MMUX. It controls the routing of incoming and outgoing data to the C/D, provides choice switches to operator, permits immediate subsystem selection and status determination, and provides random addressing of test points.

2) The oscilloscope and digital readout unit is completely and automatically programmed from information contained on the film and contains a dual trace, storage CRT. It incorporates an a.c.-d.c. digitial voltmeter with a bandwidth from d.c. to 2 Mc and capability for quadrature voltage measurement, and incorporates an oscilloscope which can be a.c. or d.c. coupled and has a bandwidth from d.c. to 10 Mc.

3) The data retrieval unit is capable of retrieving, in a random manner, any one of 10,000 frames of information, contains a film strip memory with a storage capacity of approximately 1.5 million bits in addition to the 10,000 frames of data used for visual presentation, has an average access time of 4 sec, and permits film updating by magazine replacement.

Central Multiplexer Adapter (CMA)

The CMA is located in the avionics compartment, and serves as the principal interface point for the automatic SAR's, digital computer, maintenance data recorder, printout unit, manual multiplexer, and C/D group. In addition to the MADAR internal interfaces listed previously, the CMA interfaces with the crash-data-position-indicator recorder and the auxiliary navigation computer. The CMA functions to route channel addresses to automatic SAR's, select proper SAR output, perform analog-to-digital conversion, provide power for automatic SAR's, and provide automatic test point information to the manual multiplexer.

Signal Acquisition Remote Unit—Automatic (SAR-A)

The SAR-A units are optimally located throughout the aircraft to monitor, condition, and transmit signals for selected test data points to the CMA. Each SAR-A had 30 input channels, two internal calibrate channels, a narrow band output, a single amplifier, and can provide nominal power for active signal conditioning.

Signal Acquisition Remote Unit—Manual (SAR-M)

The SAR-M units are also located throughout the aircraft to monitor, condition, and transmit test data signals to the MMUX. Each SAR-M has 30 input channels (two 15-channel groups), two calibrate channels, can provide two broad-band simultaneous outputs, is addressed by eight bits (four bits for each group of 15 channels), and can provide nominal power for active circuit-signal conditioning.

Digital Computer (DCOMP)

The computer is a general purpose 8000-word memory device which performs data compression, addresses automatic test points as programmed, determines LRU/subsystem status, performs calibration, and maintains the real time clock.

Printout Unit (POU)

The POU is an output device that provides a hardcopy record of failed LRU numbers. The POU provides an alphanumeric printout of LRU number, aircraft identification, date, time, subsystem identification, and LRU equation (for automatic test points).

Maintenance Data Recorder (MDR)

The MDR is located in the avionics compartment and records digital information regarding trend and LRU failure data. The MDR is an incremental magnetic tape recorder containing 2400 ft of tape (20 hr of recording at maximum step rate). It records in format compatible with ground processing equipment, and has tape loaded into a readily-removable cassette.

Transducers

Existing transducers, or sensors, were used to extract LRU isolation signals wherever possible. Approximately 50 transducers, however, were required for specific interface with the MADAR system. To insure compatibility and compliance with the accuracy requirements, Lockheed prepared the procurement specifications and obtained these particular transducers. As discussed elsewhere, monitored system vendors were required to provide the necessary mounting provisions.

It was determined that five type transducers would be required. These transducers were basically off-the-shelf units that had previously been used for missile applications. Minor modifications were required for airframe usage and the resulting designs are substantially superior to transducers normally found in aircraft. The majority of these are used for engine monitoring and must operate in an extremely high temperature environment. The types and characteristics are shown in Table 2.

System Software Requirements

Throughout the foregoing hardware description, there have been numerous references to computer routines, waveform patterns, and film programs. These references imply the necessity for a software development program that is equal to, or greater than, the hardware development program. Concurrent with the hardware development, an extensive effort was initiated to select test points and satisfy these software requirements.

LRU Definition

To prepare a list of LRU's to be monitored and, subsequently, to select test points, it became necessary to investigate the aircraft systems in regard to anticipated troubleshooting hours. The Lockheed Maintainability Department furnished LRU troubleshooting hours accumulated during 120,000 hr of C-130 aircraft operation. The units that rated high in troubleshooting hours were compared to LRU's on the C-5A. Since many C-5 units do not have a comparable unit in the C-130, there was not a one-to-one correspondence between the LRU's. A basis for LRU selection was established, however, and provided a general direction for LRU monitoring on the C-5.

Representatives from maintainability, reliability, safety, and subsystem design organizations jointly prepared LRU stacking criteria. Each factor was weighed and a mathematical model was prepared to assist in LRU determination. These criteria are as follows:

1) The mean elaspsed time required for troubleshooting.

2) AGE elimination, the dollar value saved by reduction of certain ground support equipment.

3) The mean time between LRU corrective maintenance actions.

4) LRU or subsystem redundancy, the degree of redundancy considering the probability of success of the mission based on MTBF.

5) Warning interval—interval between the notice of impending failure and the actual failure.

6) Onboard monitoring and tests—degree of inherent capability of LRU/subsystem to isolate failure.

7) Failure effect—determine how LRU failure affects the remainder of subsystem.

8) Cost of monitoring—sensor cost, signal conditioning complexity, and weight penalty.

With the criteria established, each subsystem design group was charged with the final responsibility of selecting LRU's for monitoring.

Failure Effects Analyses

Designers conducted thorough investigations of their respective subsystems to insure that adequate LRU isolation techniques were provided. The result of these investigations was the definition of test-point selection and assignment for automatic or manual-mode monitoring, logic diagrams for film program (manual mode), computer routines (automatic mode), determination of signal conditioning requirements, and test procedures for "nonwired" LRU's.

Test-Point Selection

The test-point monitoring capability was initially sized at 1408 total inputs with an automatic-to-manual test point ratio of 2.77:1. This configuration was derived from the C-130 LRU study, previous experience with malfunction detection systems, and engineering judgement. Although, the total number of points selected is 801 at the present time, the ratio of automatic-to-manual test points is an uncanny 2.67:1. It is anticipated that both the total number and ratio will deviate as the development program progresses.

Table 2 Transducers

Type	Range	Weight, oz
1) Vibration	0–±25g	1.5
2) Position	0–3 in.	9
	0–110°	9
3) Temperature	−100°–250°F	4
	+100°–700°F	
4) Pressure	0–40 in. Hg	6
5) Differential pressure	0–±60 psi	11

Logic diagrams

Every investigation produced a logic diagram necessary for preparation of the film program. The diagram provided test-point selection priorities for specific diagnostic routines, instrument indications, and step-by-step procedures for systematically isolating a fault. These diagrams are used principally by the manual mode but are also applicable to the automatic mode.

Computer routines

The test points selected for automatic-mode monitoring require a computer program for selection sequence and frequency.

Determination of signal conditioning

Approximately 75% of the monitored test points do not require signal conditioning. The remaining signals, however, require circuits to be designed and verified. The large percentage of preconditioned signals resulted from a MADAR interface requirement that was inserted in all procurement specifications for new hardware. The requirement insured access to test points suitable for LRU isolation and transducer-mounting provisions where a transducer was required.

Test procedures for nonwired LRU's

As mentioned earlier under malfunction detection techniques, many faulty LRU's can be isolated by clever manipulation of existing controls. The subsystem designers prepared straightforward troubleshooting routines that followed logical sequences. The procedures were placed on the film and, therefore, became standard procedures that can be accomplished by persons having a wide variation of training/experience. Approximately 1700 LRU's are monitored and 18% of these do not electrically interface with the MADAR system. The operator's detection of a failed unit by choice selection, however, does produce a record on both the POU and MDR. The apparent discrepancy between 801 test-point count and the approximately 1400 LRU's monitored by wired test points results because many LRU's utilize a combination of test-point monitoring and operational indicators.

Design Verification

The design of the hardware and software would be for naught unless an extensive verification program were instituted to evaluate the performance of the entire MADAR system from signal conditioning input to film and computer programming. To accomplish this verification, it was decided to utilize the engine test stand and the various simulators being prepared for evaluation of the other C-5 systems. The following test stand and simulators are each scheduled to accomplish a portion of the over-all verification program: 1) avionics simulator, 2) electrical simulator (*), 3) environmental simulator (*), 4) flight control, hydraulic, and landing gear simulator (*), 5) engine test stand. It was apparent that a permanent MADAR installation at each location would be idle a considerable amount of time. To alleviate this situation, a mobile MADAR subsystem (minus SAR's) was built to service the simulators marked by an asterisk. SAR units are permanently installed at each location since signal conditioning is unique for each channel. The MADAR subsystem itself will be evaluated on the avionics simulator.

Individual Subsystem Verification

The verification of the test points originating within each subsystem will follow a five-phase program. These phases can be described as follows:

1) Subsystem normal, without MADAR interface

This phase represents the normal functional testing that is performed on a subsystem when it is first received from a vendor. The signals that interface with MADAR are carefully investigated to confirm voltage levels, waveforms, etc. Although no actual interconnection is made with MADAR, this represents a significant portion of development since signal conditioning design can be initiated.

2) Subsystem normal single channel investigation

When tentative conditioning circuitry has been fabricated, signals will be individually investigated while the monitored subsystem is operated in all normal modes and with induced malfunctions. The selection of malfunctions to be induced is another fall-out from the subsystem fault analysis. This phase will also be used to obtain the waveform patterns for development of the film library.

3) Subsystem integrated with MADAR normal operation

This third phase represents the complete integration of the MADAR and monitored subsystem. The monitored subsystem will be operated in all normal modes. Both the automatic and manual modes of MADAR will be exercised to insure compatibility and observe normal operation.

4) Subsystem integrated with MADAR induced subsystem malfunctions

The monitored subsystem will be operated with systematically controlled malfunctions induced (or simulated) to verify the failure isolation capabilities of MADAR. Waveform patterns will be confirmed and test routines (film and computer) will be firmly defined. Completion of this phase will permit finalization of production signal conditioning design. Modification of design resulting from flight testing is expected to be minor.

5) Subsystem integrated with MADAR (long term, trend data collection)

This final phase will be accomplished over an extended period of time to approximate actual operation. It is anticipated that this phase will be conducted on a time-available basis after the urgency of Phases 1–4 has been satisfied.

Flight Tests

The ground verification program culminates with the preparation of the MADAR signal conditioning circuitry, film program, and computer routine for flight testing. The over-all flight test plan for the C-5 is accelerated and flight testing of the aircraft systems is distributed over the first five aircraft. Testing of the basic MADAR system, as well as most avionics systems, is to be done on aircraft No. 4. As tests are conducted on each system, the MADAR interface and its operational capability will be evaluated. The first C-5 flight tests of MADAR are scheduled for September 1968. Early flight testing of the MADAR system will be accomplished in April on a C-141 flying test bed. Although MADAR monitoring will be limited to the C-5 guidance system as installed in the test bed aircraft, advance information will be obtained in the areas of signal conditioning and waveform displays. In addition to determining the LRU isolation capability of MADAR, the flight tests are expected to finalize the film program, computer routine and provide initial evaluation of operator usage and effectiveness.

Conclusions

The MADAR system just described represents a major innovation of airborne maintenance equipment. To the casual observer, the advantages of clear text printout, continuous subsystem status indication, and immediate notification of failed LRU information, are apparent. The more astute maintenance-orientated person, however, can appreciate the advantages of incipient failure detection by long-term data analysis of trend recording.

The success of the MADAR system to convert costly unscheduled maintenance to scheduled maintenance will depend upon the exactness of the verification program conducted by Lockheed and the system acceptance by the aircraft user. The ground data reduction program must be implemented to gain full benefit from the data recorded in flight. Data information banks must be compiled and centrally located to insure that a complete history of each aircraft is maintained. Communication methods must be established to allow remote bases to use these banks for assistance in rapid turnaround. Trend data must be available to the aircraft home bases to permit failure prediction. The ultimate effectiveness of the system depends upon the planning directed toward data utilization.