DUAL-USE TECHNOLOGY: APPLICATIONS OF FLIGHT CONTROL MAINTENANCE DIAGNOSTIC SYSTEM TECHNOLOGY IN THE COMMERCIAL ENVIRONMENT

Harry Funk
John Meisner
Principal Research Scientists
Honeywell Technology Center

Abstract

First, this paper will discuss the problem that we were trying to solve with the flight control maintenance diagnostic system. Then we will present the results that one can actually achieve using this sort of system. We will present the technology elements that go into achieving that kind of result, and discuss the difference between what one would like to achieve and what is achievable. We give some views concerning what factors influence the technology transfer which so critically affects the attainable level of achievement. Finally, we will discuss the actual transfer that we've been able to achieve.

Problem Statement

The Flight Control Maintenance Diagnostic System program began in 1985. It is an effort for the Air Force Flight Dynamics Laboratory. We began this program working on the flight control system on an F-16A. At that point the flight control systems were analog. Even in the more simple analog system, there was a relatively high retest OK rate. On the flight line, a maintenance technician would remove a Line Replaceable Unit (LRU), more informally referred to as a "box". The technician would sent it back to the intermediate shop, they would run it through their automated test equipment, and about 40% of the time they were unable to find anything wrong with the LRU. The LRU would then be tagged as OK. That process is termed a Re-test OK or RTOK. What our analysis of repair records found is that the flight control system is substantially worse than other systems on the aircraft with regards to the RTOK problem. The high RTOK rate is still found as recently as 1990-91, as shown in Figure 1.

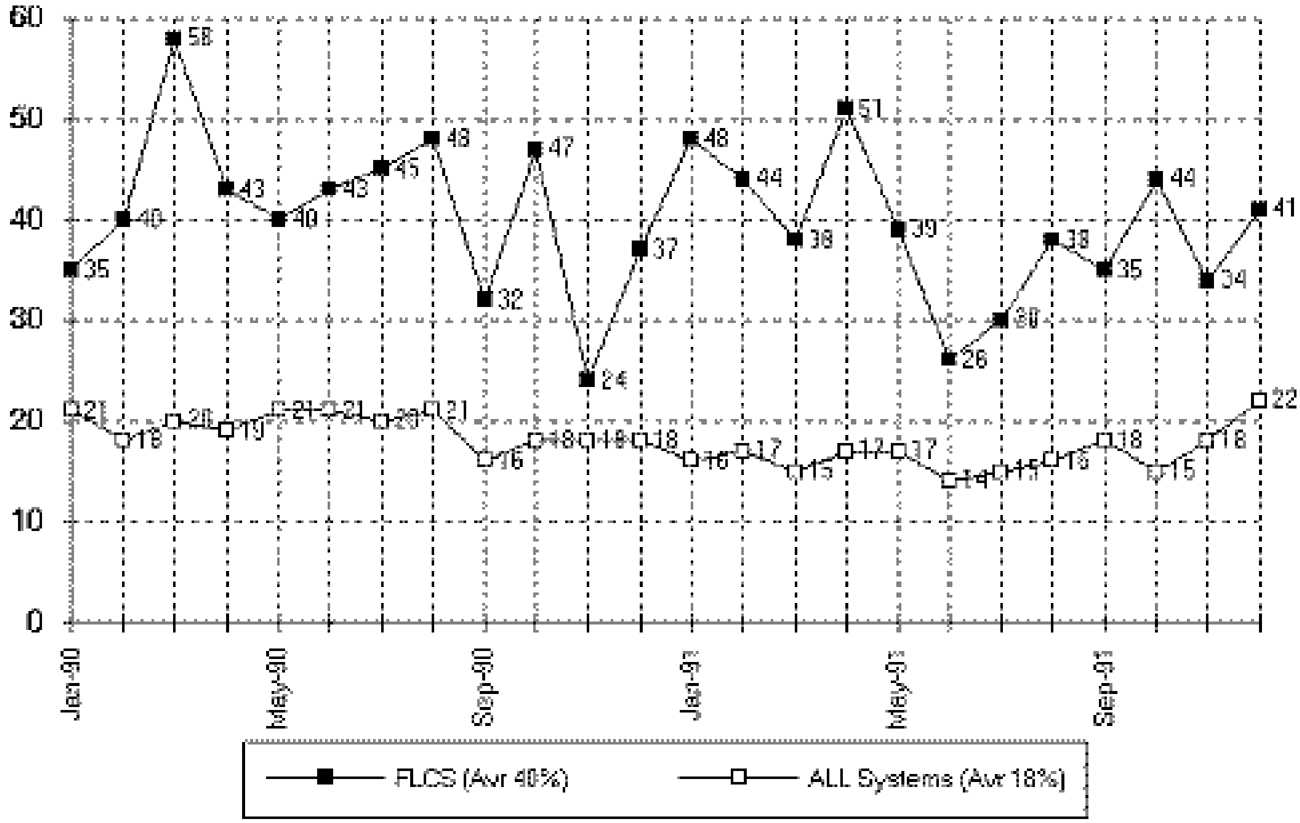


Figure 1 F-16C RTOK Rates

There are a lot of reasons that the retest OK rate is that high. One of the causes of that high RTOK rate, in our opinion, is the requirement for the maintenance technician to traverse the diagnostic information and tech orders as they are currently structured. If one looks at the tech data that exists for an F-16, it nearly fills an 8' x 10' room--floor to ceiling--it's pretty impressive mass of data. For a technician to diagnose and repair a given problem on the aircraft, the technician must access the fault isolation guides and job guides and the wiring diagrams; he's got about six books. By the time he's done getting all the information that he would actually need to repair a particular fault on an aircraft to isolate the repair, he's probably got about eight books and has only about ten place holders (fingers), which doesn't work well.

The other factor that one tends to find even given this massive amount of technical information is that if one tries to diagnose a particular problem using this technical information, one doesn't always find the answer. The reason for that is intrinsic to the nature of the paper documentation. To maintain a reasonable volume, (even a small roomful of information), one must draw the line somewhere for what failure cases one will consider and document. The structure of the fault isolation guides is a tree. one begins with a fault tree, which covers all of the considered cases. A set of symptoms defines a starting point on a tree and subsequent actions allows one to make decisions that will follow one branch or another. At some point, though, one "falls off the bottom" of the tree. This happens when the problem that the technician is diagnosing is considered so rare that it is not handled in the technical information.

In other cases, the technical information may contain errors. In a recent field test, we injected a number of failures into the flight control system by means of a breakout box, and then tried to track them down using the technical information. About 70% of the time the current fault isolation manuals will not diagnose the right failure.

Field Test

The obvious question then is, "Given a different approach, how good a job can one do?" In order to provide an initial answer to that question, we performed a field test at Luke Air Force Base looking at the following elements. First, we wanted to make sure that we could interface with the bus on the aircraft -- a 1553 bus. We wanted to extract some flight control system signature data--what it looks like when there's a particular class of faults. We want to use a fault isolation manual to see how well technicians perform with a given type of fault, test the FCMDS approach, enhance that approach based on what technicians reported back to us, then go through a more extensive comparison test.

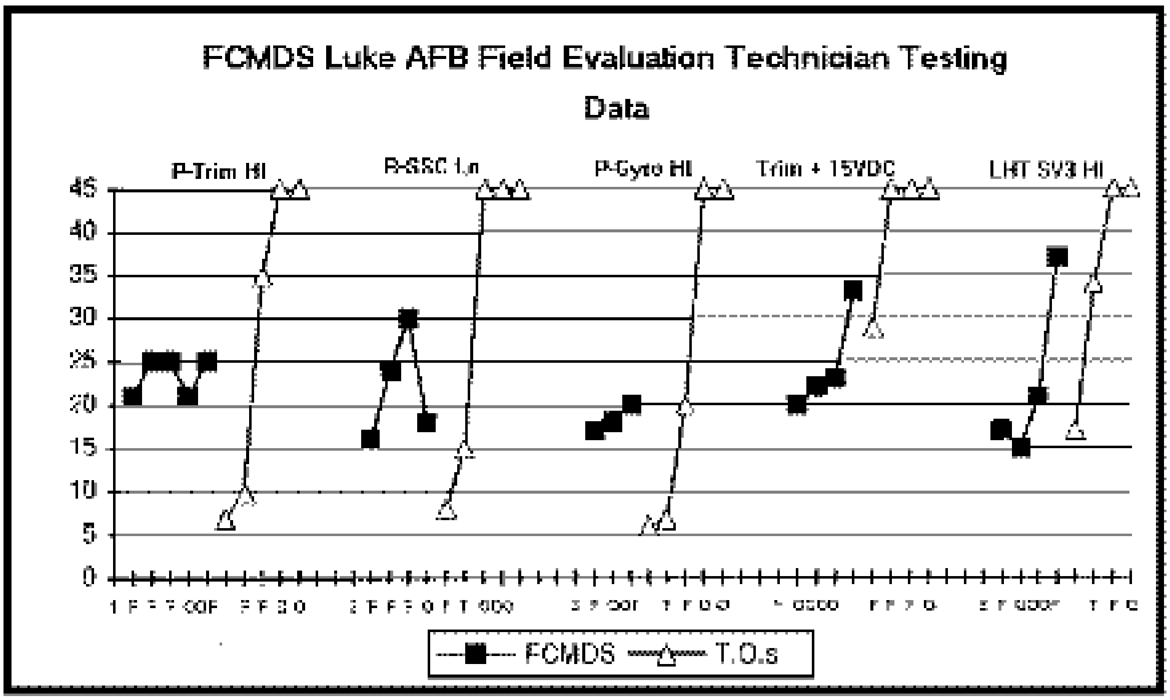
Validation

In the FCMDS system we take the representations of the procedures found in the Air Force technical orders and reauthor them so we have an electronic format of the same data. Thus, the information presented has, in most cases, the same content. The underlying reasoning process, presentation and aiding capabilities have been altered substantially, however.

When one changes the content or presentation of technical data one must validate that one has not made any adverse, substantive changes (i.e., negatively affecting safety or correctness) to that technical information. For our program, since we were testing in a constrained maintenance environment, this validation consisted of review of the procedures with a General Dynamics Flight Controls expert, Terry Hay, and an Air Force Engineering Technical Support (AFETS) engineer, Dave Lafferty. Though not a part of our original field test plan, while we were at Luke Air Force Base for the field test, actually we assisted the maintenance staff with a number of diagnostic problems that were troublesome.

Technician Evaluation

Evaluation Design. The primary purpose, of course, was to perform a set of technician evaluations. The technician evaluations that were conducted as follows: we gave the technician the FCMDS unit, a ruggedized portable computer, and gave him a twenty to thirty minute training session. Essentially, we had the technician work through a diagnostic problem using our system. This example problem was not one of the ones that was in the test set. Then we injected a failure into the flight control system using breakout boxes, junction boxes which fit between connectors in wire harnesses to allow easy access to the signals traveling in the wire harnesses. We would then tell the technician what he would have seen as the results of a pilot debrief. When a pilot returns from a flight and reports a problem (squawks), he provides a set of Master Fault List (MFL) codes, which indicate the nature of the problem and symptoms he experienced in a standardized format. We provided the technician with this set of MFL codes, and observed what the technician does using their "standard technical procedure" and then the FCMDS box, using a balanced experimental design. The results of the testing are summarized in Figure 2.



F = Flight Controls Technician

O = Non-Flight Controls Technician

Figure 2

It is notable that there are a lot of test cases in which the time was forty-five minutes. The reason for this improbable result is that if a technician was not approaching a solution (for example, the technician was examining the wrong branch of the flight control system) after forty-five minutes of running the test, we would terminate that trial. The intent of the time limit was to not frustrate the technician unnecessarily. Typically when a technician who's not experienced in the flight control domain runs into a problem that he can't solve, the technician will find the chief and the chief will help him work through the problem. Since in this field test one of the factors we wanted to assess was the extent to which FCMDS could help an inexperienced technician approach an expert's performance, we required that the technician diagnose the problem working alone.

The evaluation data compares a technician's Standard Troubleshooting Methodology (STM) performance to his performance using FCMDS, for two technician skill levels: 1) flight controls experienced and 2) flight controls novice (which includes junior technicians and technicians with avionics experience. Many of the more flight-controls experienced technicians didn't use the tech orders at all, thus it would be inaccurate to term the non- FCMDS sessions "TO use". For some of the cases flights control technicians were able to isolate the problems very quickly. The diagnosis time across test cases suggests that there is a range of difficulty, with case #1 the easiest, and #5 the most difficult. One sees that these cases were a little bit more difficult.

Figure 3 shows a technician trying to use the technical manuals. He has five places marked in the manual, so that he can maintain his place while flipping back and forth between pages. Since he's using his other hand to command BIT, that leaves him with one hand too few to flip through the data. Figure 4 shows the technician using the FCMDS unit.

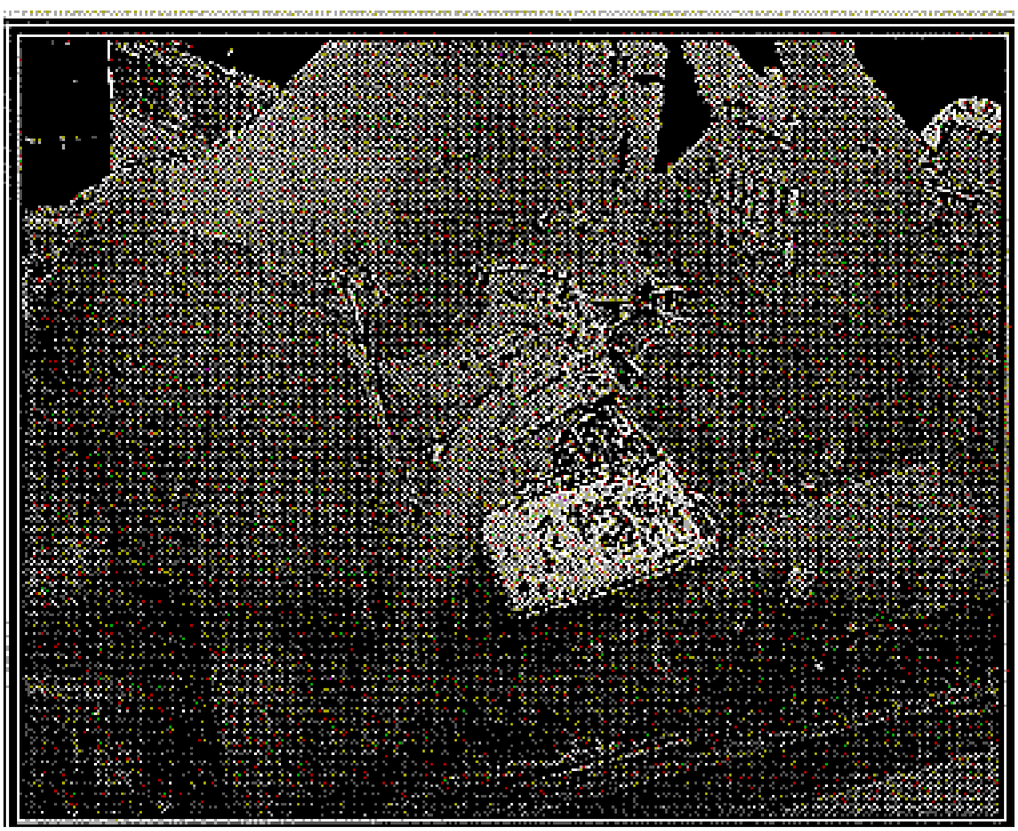


Figure 3 Technician using STM

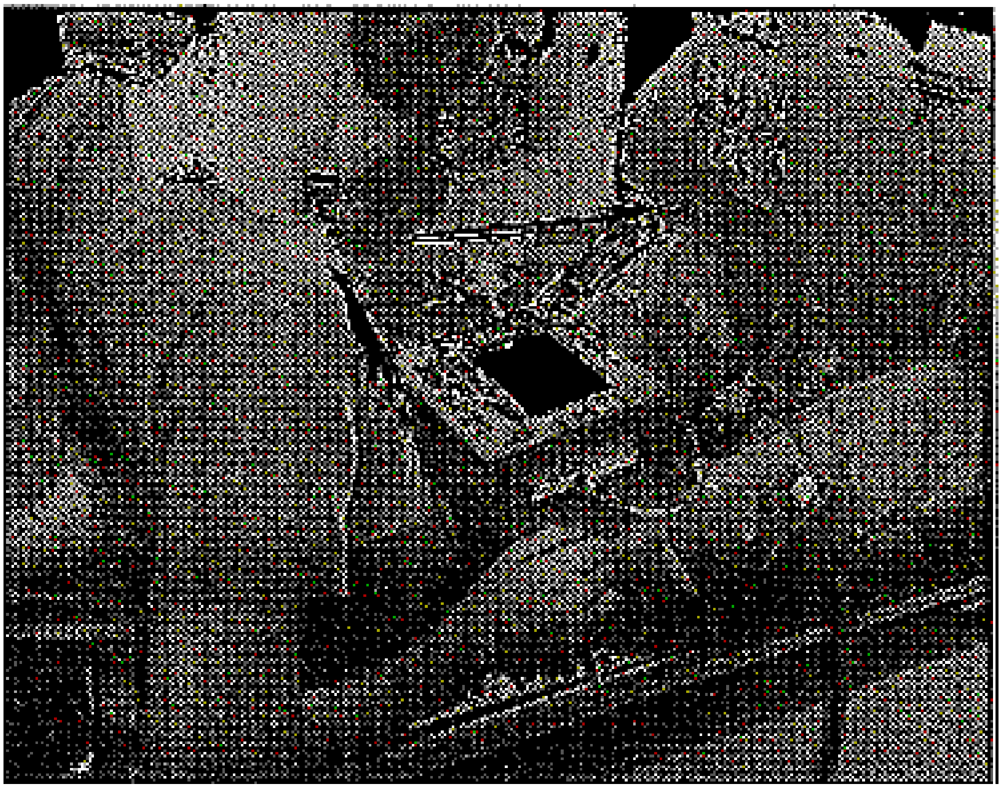


Figure 4 Technician using FCMDS

Evaluation Results. The performance of flights controls experts is quite reasonable for this task; they correctly isolate the problem in eleven of fourteen trials. Unfortunately, non-flight control technicians were only able to isolate the problem in one of nine trials. In all, the technicians were able to find the problem in twelve of twenty-three trials using the STM. Isolation time shows a similar pattern. The flights controls experts averaged twenty-three minutes; non-flight-control technicians were very close to the forty-five minutes limit (there was one technician who isolated the problem in less than the forty-five minutes allotment).

When using the FCMDS unit, all technicians were able to isolate the problem in a more uniform and reduced amount of time. That average time, in fact, matched the performance of the flight controls experts.

The final factor that we consider notable in the evaluation results is a comparison of false pull rate between the STM and FCMDS conditions. A false pull, in our evaluation scenario, is the removal of a LRU which is not faulty. In our case, since we knew the symptoms and faults a priori, that is the same as saying the LRU was not indicted by the symptoms. False pulls are the result of a troubleshooting technique for which the denigrating term is "swaptronics". In this technique, LRUs are removed and replaced to assess their correct function. While this may be a fast means of assessing correct operation, it is expensive. Once a technician removes the LRU, it has to go back through the system to be checked out and recertified before it can go back on an airplane. That has severe implications in terms of the spares requirement, what the Air Force has to maintain in back stock. The expert technicians had eleven false pulls, and there were twelve among the non-flight-controls technicians. There were no false pulls with the FCMDS unit.

Payoff

If the performance improvement that was seen in the field test evaluations were indicative of the benefits which would be realized across organizational maintenance units, a quick calculation shows the savings would amount to over 2200 hours per month for the F-16 flight controls alone. This calculation uses conservative estimates for reduced false pulls, and diagnostic time reduction. It does not take into account other savings which are consequences of the reduced false pull rate, for example the reduction in Avionics Intermediate Shop (AIS) testing, or the reduction in prime system spares, assuming an 80% reduction in false pulls, and a 25% reduction in diagnostic time.

Technology Elements

Technology elements are the concepts and techniques which taken together, form the basis for the FCMDS system, and provide a means to achieve the sort of performance improvement we have presented here. We will discuss several of these technology elements in turn.

Diagnostic Reasoning: The Fault Tree

Diagnostic reasoning using current Technical Orders (TOs) uses a fault tree. Each node in the tree corresponds to a certain state of information. Information collected at a node leads the technician to examine a branch of the tree. Leaf nodes correspond to an identified fault, or to a group of fault cases considered rare enough to not be worth expanding. This grouping of rare fault cases serves to constrain the set of TOs to a manageable size, with the undesirable effect that further diagnosis is the responsibility of the technician. Such groupings are commonly associated with the instruction, "Refer to schematic". The fault tree represented in current TOs is static, or predetermined. As failures of one type or another are found to be more common, changing the fault tree to reflect that change in probability of occurrence requires a major re-write of the TOs, something which is rarely undertaken.

In contrast, FCMDS is able to generate the next level of the fault tree dynamically. The FCMDS unit maintains the state of the diagnostic session, i.e. the information collected thus far. Given this information, FCMDS can determine a set of suspect components which could be responsible for the observed symptoms. FCMDS then scans all available tests to determine the test which (at this point in the diagnostic session) would provide the most information for the lowest cost. In a sense, then, FCMDS dynamically selects the best node to hook to the tree, attaches it, and suggests that test to the technician. The technician can override the recommendation and attach another test (node) at the current location. In order to assess the significance of the test which is then run by the technician, FCMDS uses a model of the flight control system to interpret a passed or failed test.

The System Model

The model of the system that FCMDS maintains is simply a representation of the functional dependencies in the system. Each Line Replaceable Unit (LRU) is decomposed into its functional elements, or sub-LRUs. FCMDS connects the inputs and outputs of these functional units (and LRUs) to determine the functional dependencies.

Our system covers 74 LRUs which comprise some 4,300 functional elements and about 12,000 signals. The model is used to interpret the outcome of diagnostic tests by associating a functional path through the model with a test. When the test fails, some element on that functional path is asserted to be failed, though it is unknown which specific element is indicted. Another test is selected which exercises some, but not all, of that functional path, and the overlap is either doubly indicted (if the test fails) or cleared (if the test passes). When all of the multiply indicted functional sub-paths lie in the same LRU or wire, the bad system element has been found.

Test Selection

At any given point in the diagnostic session there are a number of potential suspects. What FCMDS is designed to do is reduce the size of that set to one suspect. FCMDS examines the set of suspects and signals that those suspects use. For each available test, FCMDS determines whether the test examines any of the suspect signals. If so, the test is deemed applicable under the current circumstances. If not, the test is eliminated from consideration.

The test to recommend is selected from this applicable set by performing a (simple) cost- benefit analysis. Essentially, it is desirable to conduct a binary search, eliminating as close to half the suspects as the set of applicable tests will allow at each step in the diagnostic session. We have experimented with complex schemes which take into account the number of people required, the test duration, and how easy it is to conduct the test, based on the current state of the aircraft (e.g., is a panel removed which makes a particular test much easier). FCMDS must maintain a knowledge of the aircraft state to be able to instruct the maintenance technician what "clean up" actions remain at the end of a diagnostic session. The more complex information theoretic analyses are not used in the current system, since they are found to have little benefit over a simpler test prioritization scheme.

Technician Aiding

In addition to tracking the state of the system for maintenance clean up, we provide other forms of aiding to the technician. The aiding is structured so that the technician can call up help at any point, but is not presented gratuitously for the more advanced technicians that do not require assistance. This aiding can take the form of additional instructions (i.e., sub- procedures which comprise a single step in a parent procedure), graphics which locate references within a procedure (e.g., the location of the BIT switch on a panel, and the location of the panel in the cockpit), or schematics which explain a signal flow path.

Wiring

One of the features that is incredibly popular in the FCMDS system is the wiring display window. An example of the wiring display window is shown as **Figure 5**. The technical information in commercial or military manuals that supports wiring diagnosis is tabular data. It is quite challenging to use this tabular data to trace a wire path through the aircraft. At one point, Paul Bursch, our lead field test engineer, was tracing a wire path. He took twenty minutes to track through a particular wire path. At the end of that period of time, he found out he was on the wrong wire. He had made an error in tracking through the effectivity codes.

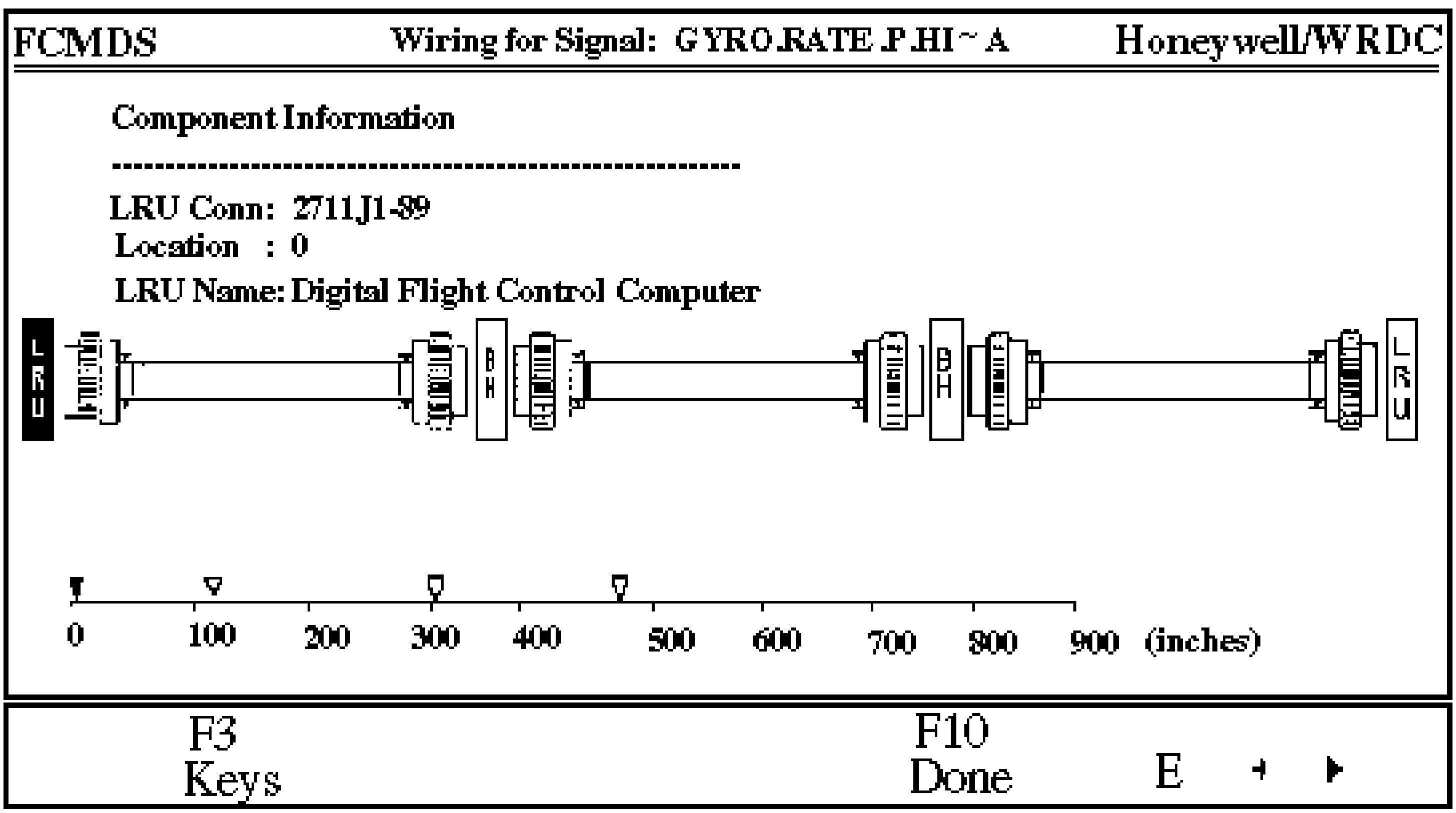


Figure 5 Wiring Display Window

Our system accesses a wiring database to generate a graphic representation of any wire path in the system in less than twenty seconds. Using the arrow keys, one can flow through the wire path from connector to wire to connector. In each case one will gain information about what pin and connector the signal of interest is on, so the correspondence to observable physical characteristics is maintained.

FCMDS also provides a time domain reflectometer (TDR) trace for the wire path. Essentially if the technician pings the wire, a TDR trace shows the places that the technician would expect to see returns. Typical reasons for returns are places where the wire path went through a bulkhead or through a connector. If the technician sees a return at any other location, that is an anomalous condition that needs to be investigated.

Constraints on Technology Transfer

We have field tested the FCMDS unit and, under a constrained scenario where we ran five test cases, we've proven the worth of the system. The technology we developed under the FCMDS program is somewhere beyond a laboratory system, but short of a production product. Why, if this technology is useful, does it not immediately get implemented? One phrase which comes to mind is, "a square peg in a round hole."

Actually, the situation, while of that nature, is far more complex. FCMDS is a packaged solution. In order to support that packaged solution, there are requirements on the infrastructure, such as the authoring of technical data, the capture of the model, and so forth. Most organizations, including the Air Force, are understandably reluctant to undergo such large changes with the consequent disorganization that results. What happens instead is that selected pieces of the solution, or, as we have termed them, "technology elements" will be adopted and applied. We have seen this happen in a variety of domains. In the commercial airline domain, the diagnostic approach used for FCMDS was modified and forms the basis for the Boeing 777 Central Maintenance Computer (CMC). Other elements of FCMDS, such as the technician aiding approach, were not used due to the difficulty of modifying the way that technical data is authored and distributed today.

The decisions as to whether or not a particular technology element will be a part of the solution for a new application domain are of course driven by projected costs and benefits. For the Boeing 777 CMC, some diagnostic system had to be built. We asserted that maintaining the data for the diagnostic system is more easily done when the data has the same structure as the system. Our functional model has that form, so that if one makes design changes in a particular LRU, one has to change only the model for that LRU.

Other problems that are typically faced when trying to introduce this technology into a new application domain are concerns over the external visibility into an LRUs performance. When one builds a flight-critical/safety-critical kind of system, one typically wants to build a "wall" of sorts around the equipment. One wants no other systems to interfere with what the system is doing. From the diagnostic perspective, this is an undesirable state of affairs, because the diagnostic system wants to know everything that is going on inside the safety- critical system. There is a tension between having good subsystem boundaries, and being able to provide meaningful information on system health which improves the performance of the system as a whole.

In spite of these limitations, and others like them, we have now successfully applied these concepts to factory test, LRU diagnostics, commercial avionics suites, military flight controls, and space avionics. Certain elements will also be incorporated into the F-16 Integrated Maintenance Information System (IMIS) project now underway.