EVALUATION OF FAILURE DIAGNOSIS IN CONCEPTUAL DESIGN OF MECHANICAL SYSTEMS

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ABSTRACT
This paper discusses a methodology for improving quality and reducing life cycle costs of mechanical systems. The principal concept is that a system can be designed, in the conceptual stages, to be easier to diagnose for failures. To perform this, functional decomposition and form-to-function mapping are utilized to demonstrate the relation of design to diagnosis and for diagnosis itself. Four diagnosability metrics are developed and four hypothetical conceptual designs are evaluated for diagnosability and compared. An example is presented wherein three conceptual designs for a toolhead positioning system are evaluated for diagnosability at two levels of abstraction and the results compared. The area of design for diagnosis offers promise in improving system quality and reducing life cycle cost; research is continuing to refine and integrate the procedures with other aspects of the concurrent engineering design process.

1 INTRODUCTION
In an increasingly competitive global marketplace, the success of a product depends on that product delivering maximum functionality at minimum life cycle cost. A product that meets or exceeds the functionality expected by a customer, at low cost, is generally considered to be of high value. Recently it has been recognized that much of the value of a product is determined during the design of the product. There has been extensive effort directed toward designing value into a product, leading to the concept of concurrent engineering: the concurrent consideration, throughout the design process, of all aspects of the life cycle of a product. Most of the effort has been directed toward the consideration of the manufacturing and assembly aspects of a product during the design process. Receiving somewhat less attention, particularly for mechanical systems, has been consideration of the reliability and maintainability (RAM) of a product during the design process. One of the most important aspects of RAM is the diagnosability of a product, the measure of the ease of diagnosing the cause of any loss of functionality.

Most products which incorporate mechanical systems are not 100% reliable; they will eventually fail in some way and require repair. Before a product can be repaired, the cause of the failure must be diagnosed to ascertain what corrective action is needed. The time required for diagnosis often accounts for a large part of the repair cost. One study, on CH-54 helicopters, determined that fault isolation required one-third of the average corrective maintenance task and that the cost for fault isolation (in 1980) was $25 per flight hour (Cook, 1980). Another source estimates failure
detection and isolation requires 50 percent of the repair time (Bozic, 1985). A third source simply states fault isolation requires the "preponderance of the repair time" (DoD, 1988).

Diagnosability directly affects the value of a product. "Any product that can advertise reduced downtime is a highly desirable product. Most customers are willing to pay extra if they are convinced it means less maintenance." (Raheja, 1991) Loss of value results from both the loss of functionality and the cost of the diagnostic process. The loss of functionality results in the customer not receiving the functionality that is expected from the product during the time that the cause of this loss is being diagnosed. A study by the Boeing Company showed for a fleet of 100 commercial aircraft, the cost of technical delays due to fault isolation is about $2M per year. This accounts for only the tangibles such as direct revenue loss because of passenger transfer, expense caused by increased handling of passengers and cargo, and extra crew salaries. The cost of maintenance attributable to fault isolation alone adds another $4M per year. (Standen, 1982)

Because the cost of diagnosis is proportional to the effort required, either in time or expertise, increased difficulty in diagnosing failures results in higher repair costs. As products become more complex, they become increasingly difficult to diagnose; thus, the time to diagnose the system and the possibility of an incorrect diagnosis both increase. A product that was designed with increased diagnosability would be easier to diagnose, would therefore yield full functionality for a greater portion of its life and possess a lower life cycle cost, and thus would be of higher value than one that was not designed for increased diagnosability.

This paper discusses methodologies for increasing the diagnosability of mechanical systems. Current methods are addressed in Section 2. Form-function mapping is explored as it applies to design and diagnosis in Section 3. Section 4 describes the evaluation of diagnosability in the conceptual design phase. Section 5 describes the application of the diagnosability evaluation methodologies to a toolhead positioning system. Section 6 concludes the paper and outlines the work to be done to enhance the concept of design for diagnosability.

2 CURRENT METHODS

The idea of creating a system that is more diagnosable is not new. Other fields of engineering, especially digital electronics, have already done so. For mechanical systems the approach has been to add diagnostics to the system or borrow concepts from other areas of engineering. Incorporating diagnosis into the conceptual design of mechanical systems has received little attention.

2.1 Sensor Based Diagnosis for Mechanical Systems

Most of the work in diagnosis of mechanical systems has been in the area of automated sensor based systems. This is often referred to as built-in test (BIT), and is performed by built-in test equipment (BITE) or automatic test equipment (ATE). The diagnosability of a system is increased by adding sensors to the system, or extracting more information out of the existing sensors. Examples of this can be found in (DoD 1988) and (Ribbens 1990). Often times BIT will be applied to the control circuits of mechanical systems. In this manner, mechatronic systems can also incorporate fault tolerance (Loeckner, 1990; deBenito, 1990; Umeda, 1991). BITE or ATE are added onto the system, however, rather than being "designed in" as in electronic systems. This adds system complexity and can reduce reliability. (Bozic, 1985; Cook, 1980)

As the systems to be diagnosed become larger and more complex, the trend has been toward automated diagnosis through knowledge-based (or expert) techniques in general (Harmon, 1985), and model-based techniques in particular (deKleer, 1987; Paasch, 1991; Scarl, 1987). Although research in this area has shown substantial progress in understanding the diagnostic process, it generally deals with adding automated diagnosis to existing systems.

2.2 Application of Reliability and Maintainability Engineering

There exists a considerable body of research work in the area of reliability and maintainability (RAM), particularly as applied to military systems. The reason for this is that the U.S. government contracts these efforts as a part of a development program and pays up front for the desired results (Jones, 1988). This includes the above mentioned work in fault tolerant design,
BITE, and testability, as well as the related areas of knowledge-based systems for reliability assessment.

The broad definition of maintainability would include diagnosability, but the majority of RAM work deals with reliability, readiness assessment, and other forms of analysis of existing systems rather than evaluation for the purposes of design improvement, particularly at the conceptual design phase. Present methodologies for maintainability analysis are usually applied "after the fact." For example, (CALS 1989) begins the RAM process, "Post Design Review." Examples of methods used are fault tree analysis (FTA), and failure modes effects analysis (FMEA) or failure modes effects and criticality analysis (FMECA) (Bellinger, 1988; Kapur, 1988; Raheja, 1991; Smith, 1973). The use of FTA is restricted because each fault tree is specific only to the identification of system elements and events that lead to one desired event (Kapur, 1988). Though currently only applied to systems in the embodiment phase of design, FMECA has potential for application in the conceptual design phase as well.

There are a few design guidelines resulting from RAM research that can potentially be applied to diagnosability. Included in these are: simplification, modularity, and accessibility. Presently however, these guidelines tend to be too general to be of use in improving diagnosability. In addition, because of the heavy reliance on electronic control of mechanical systems in military applications, references such as (Jones 1988) consider mechanical design to be the packaging and the connections of electronic hardware.

3 DESIGN FOR DIAGNOSIS

Diagnosis is the process of determining the parameter(s) whose respective parameter measure(s) is (are) not at the intended design state but at some state which causes a failure in the system (loss of functionality and performance measures not meeting requirements). To design for diagnosis, the designer would make the process of determining the parameter(s) not at the design state easier to perform. Once the parameter(s) not at the intended state are isolated, a repair action takes place to return the failed parameter to the design state. To accomplish repair, accessibility must also be considered. A discussion of repair and accessibility may be found in (DoD 1988) and others. The following sections discuss how diagnosis can be improved by selecting the structure of the system hierarchy.

3.1 Design by Function

Products are composed of design objects that supply specific functions which when combined, satisfy the product or system function. When performing top down conceptual design, a functional decomposition is often performed (Ullman, 1992). This action creates sub-functions that are satisfied by a design object containing a specific group of parameters. If the function-parameter sets are kept independent of one another, then the diagnostician can trace down the hierarchy easily to locate the failure. A diagram of this type of system is shown in Figure 1. In Figure 1 each of the system functions (Fs) are decomposed into sub-system functions (F). Each F has a performance measure (PM). These Fs are satisfied by design objects (shaded boxes) containing parameters (P). Each system function maps to a unique set of subsystem functions, and each subsystem function maps to a unique set of parameters. In diagnosing the system of Figure 1, three performance measures would be taken to locate the design object outside the design state. After that, the three parameters contributing to that performance measure would have to be measured. If multiple sub-systems were at fault each of their parameters would have to be tested. For a single fault, in this system a maximum of six measurements would be required for fault isolation (three performance measures and three parameter measures). This type of design, maintaining the independence of parameter sets that satisfy one function, is what Suh (1990) refers to as "ideal" design.
If a system were designed such that each of the design objects contributed to each of the functions, this system would be represented by the diagram in Figure 2. With a system such as this, taking performance measures to determine which sub-system had failed would provide no useful information. The only way this system could be diagnosed is to take individual parameter measures. The system of Figure 2 would require a maximum of nine parameter measures.
In many systems, performance measurements are already built-in, in the form of gauges, indicator lights, and meter readings. Performance measures can usually be taken without disassembling the system. Parameter measures on the other hand, often require the system to be shut down and disassembled. If the failed sub-assembly is identified, less disassembly is required and diagnosis time is reduced. The system of Figure 1, with a maximum of six measurements, three of which are performance measures, should in general be easier to identify faults in than the system of Figure 2. In summary, systems that maintain independence of the parameters that satisfy individual functions are generally more diagnosable than those that do not.

3.2 Alternative Concept Modeling
When performing conceptual design, often a number of different alternative concepts are considered. These concepts are then evaluated against one another or some benchmark. It is during this evaluation step that the diagnosability of the concept systems is to be considered. The function/performance measure-parameter relationships will exist on different levels, dependent upon the level of abstraction of the system concepts, as will be demonstrated in section 5.

In this section, four competing concepts for a hypothetical system, which accomplish the same functions, will be introduced. The four systems are represented by Figures 3 a, b, c, and d, and are assumed to be at the same level of abstraction. Figures 3a, 3b, and 3c accomplish the same number of functions with the same number of parameters and the same number of function/performance measure-parameter relationships. The system represented by Figure 3d accomplishes the same number of functions/performance measures but maintains the independence of performance measure-parameter hierarchy as discussed in section 3.1. The result is that the system of Figure 3d requires 21 parameters to provide the same number of performance measure-parameter relationships and hence functions, the other systems required only 10 to accomplish. This is representative of the fact that to maintain the independence, parameters that contribute to different performance measures cannot interact and therefore some parameters which could be combined in other systems are not.

![Diagram](Image)

Figure 3a: A System with Various Levels of Function/Performance Measure-Parameter Interrelationships.
Figure 3b: A System with a Greater Number of Function/Performance Measure-Parameter Interrelationships.

Figure 3c: A System with a Limited Number of Function/Performance Measure-Parameter Interrelationships.
4 MEASURING DIAGNOSABILITY OF COMPETING SYSTEMS DURING CONCEPTUAL DESIGN

In this section, the four competing concepts introduced in section 3.2 will be evaluated for diagnosability. A methodology for evaluating competing systems is developed and applied to the example systems. The systems are also further discussed as to their diagnosability.

Throughout the example analysis, it is assumed the performance measures are readily available and the "cost" of performance measures is negligible compared to that of parameter measures for a couple of reasons. In real systems usually some disassembly is required to make a parameter measure and once the parameter is made accessible, test equipment external to the system must be used to make the measurement. This means for each parameter measure there usually is system shutdown time, parameter access time, and actual parameter measure time. The cost of each of the parameter measures is assumed to be equal even though in real systems this is often not the case. Different parameters will require different equipment to measure them and the accessibility often varies substantially.

4.1 Analysis of Diagnosability

The analysis of the systems can begin in one of two ways. First, a fault tree analysis (FTA) could be performed to identify the parameters (P) causing the performance measure (PM) to be outside the design value. Then the effects of the failed parameter could be incorporated, such as done in failure modes and effects analysis (FMEA), to determine the interaction effects from the performance measure-parameter relationships. One can ask the questions: "In order for this function to be present, what parameters must be at their design state?" and "If this parameter were to fail, what performance measures would be affected?" The second way would be simply to begin with the FMEA step. The steps performed at this point can be used later as the basis for FMEA or FTA once the design reaches the product stage. Because the physical embodiment of the conceptual design affects the outcome of FMEA and FTA, these techniques must be reapplied once the design becomes a physical entity. After completing either method, one has to relate the common parameters to performance measures using a set of rules. To perform the former method above, the analysis begins with a performance measure which is outside its design state and the parameters which make up that performance measured are considered as candidates. Other performance measures with parameters common to the performance measure outside the design
state are considered and the candidate parameters are isolated to determine the number of parameters that must be measured to locate the failed parameter. The result of the analysis done in this method for the system of Figure 3a is follows:

1) If PM1, PM2, and PM3 are outside the design state then P1 and P2 are candidates. Total candidates: 2

2) If PM2 and PM3 are outside the design state then P3 and P4 are candidates. Total candidates: 2

3) If PM2, PM3, and PM4 are outside the design state then P5 is at fault. Total candidates: 1

4) If PM4 only is outside the design state then P6 and P7 are candidates. Total candidates: 2

5) If PM4 and PM5 are outside the design state then P8, P9, and P10 are candidates. Total candidates: 3

4.2 Evaluation of Competing Systems on the Basis of Diagnosability

A rating system has been developed to take advantage of the analysis of Section 4.1 to determine which system has better diagnosability. There are four measures of diagnosability which are applied to the systems of Figure 3 and the result shown in Table 1.

<table>
<thead>
<tr>
<th>System</th>
<th>MNPM</th>
<th>PMC</th>
<th>SIC</th>
<th>ANPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>3a</td>
<td>3</td>
<td>10</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>3b</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>3c</td>
<td>2</td>
<td>21</td>
<td>6</td>
<td>1.67</td>
</tr>
<tr>
<td>3d</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4.2</td>
</tr>
</tbody>
</table>

The first measure of diagnosability is the Maximum Number of Parameter Measures (MNPM). This metric is the maximum of the number of parameter measures required to verify which parameter is at fault in a failed system after performance measures have been taken. It is desirable to have a system requiring the fewest number of parameter measures, therefore in this case, system 3b would have the highest diagnosability by this metric. For any system, the fewer parameter measures required, the more diagnosable the system.

The second measure of diagnosability is Parameter Measure Cost (PMC). This metric takes into account the total number of parameters to be measured in the system and the measurement difficulty (Fd) of each one. For example, the Parameter Measure Cost for the system of Figure 3a is calculated from the example as follows:

\[ \sum_{i=1}^{n} Fd_i = \text{ParameterMeasureCost} \]

\[ Fd_1 + Fd_2 + Fd_3 + Fd_4 + Fd_5 + Fd_6 + Fd_7 + Fd_8 + Fd_9 + Fd_{10} = 10 \]

For the example systems of Figures 3a, b, and c, the measurement difficulty and number of parameters was kept constant for illustration. For all four cases, a Fd of unity was used. When calculating this metric for competing systems, the design engineer could assign a relative Fd, with a value of 5 being most difficult and 1 being easiest.

The third measure of diagnosability is the System Interaction Complexity (SIC). This metric is used to determine how much rule information about the system the diagnostician, whether human or computer, must have beforehand to be able to immediately isolate the cause of the system fault.
System Interaction Complexity is determined by the total number of "If" statements or "rules" relating performance measures to parameter interactions. For the example analysis of System 3a, in Section 4.1, there are five "If" statements; therefore the System Interaction Complexity is five. While complete a priori knowledge of the performance measure/parameter interactions is required for all four systems, there exist differences in the complexity of these interactions. As can be seen from Table 1, the system represented by Figure 3b has the highest System Interaction Complexity. This means the most complex a priori knowledge of both the system and the function/performance measure-parameter hierarchy must be known for diagnosis of this system. The system represented by Figure 3d on the other hand would require much less complex a priori knowledge of the system because there are no interactions between function/performance measure-parameter sets; hence, the System Interaction Complexity is low. The only rules required for System 3d would relate which parameter-set makes up each performance-measure. This information must be known and the parameter measure cost for this type of system is much greater. Which type of system to choose will be discussed in section 4.3.

The fourth measure of diagnosability is the Average Number of Parameter Measures (ANPM). This metric is a combination of two other metrics: the Parameter Measure Cost divided by the System Interaction Complexity. This metric gives an indication of the average amount of ambiguity the diagnostician may face in diagnosing the system, and is similar to the Maximum Number of Parameter Measures metric in that a system with a low Average Number of Parameter Measures is desirable. Again, in this case, system 3b would have the highest diagnosability by this metric.

To rate a number of competing systems on a diagnosability only standpoint, one would rank the systems by considering the following: first, a system with the lowest MNPM; second, a system with the lowest ANPM; third, the lowest PMC; and fourth, the lowest SIC. Systems with low values for MNPM and ANPM will require fewer parameter measurements to isolate a fault for the worst and average case respectively. With the assumption that parameter measurements are relatively expensive (per 3.1), these systems would be less expensive to diagnose than those with high values for MNPM and ANPM. Low values for SIC represent lower requirements for a priori knowledge of the system, but come at the cost of higher values for ANPM. These trade-offs are further discussed in the next section.

4.3 Choosing a System on the Basis of Diagnosability

To choose which system to develop into a product from a diagnosis standpoint, the method of diagnosis, the diagnostician, the cost of downtime, the field replaceable unit (FRU) level, and the level of manufacturability of the system must all be taken into account.

For a system to be designed for diagnosability, the abilities of the diagnostician must be considered. The amount of knowledge the diagnostician has about the system is also very important. Systems designed to maintain independence of function are best for non-experts. This allows for a topographic diagnosis strategy (Toms, 1989) which is based solely on system structure and is preferable when experience on a system is minimal. From the systems of Figure 3, only system "d" maintains independence of function. This does disagree with the ranking of section 4.2; however, a system with a high System Interaction Complexity would cause considerable difficulty for a non-expert diagnostician. Often during diagnosis, once the sub-system which contains the failed parameter is located, diagnosis becomes more difficult and is often (poorly) performed by removing and replacing each parameter or component that contains that parameter until the problem is resolved. Because of this, often there is a tendency to replace all candidate parameters, whether failed or not. It might be best to combine all parameters that contribute to the performance measure in each sub-system of a system such as represented by Figure 3d into a single FRU. The result is a system in which no parameter measures would be required. The result is illustrated in Figure 4. The System Interaction Complexity would remain the same as it was for the system of Figure 3d but the Parameter Measure Cost and Maximum Number of Parameter Measures would be zero. This type of system would be highly rated by the ranking of section 4.2. Reducing or eliminating the need to take parameter measures reduces diagnostic time. Without having to take parameter measures, there would be no need to
disassemble the system below the FRU level. The time required for measurement of parameters and their possible adjustment would also be eliminated. A system designed for manufacturability reduces the number of replaceable components and therefore the required number of parameter measurements. For the novice diagnostician, when choosing between competing systems, the system with the lowest System Interaction Complexity should be chosen and if possible, the parameters combined into FRUs.

![System](image)

Figure 4: A System with Independence of Function/Performance Measure-Parameter Relationships Incorporating Modular FRUs.

Systems designed for expert diagnosticians can be designed to take full advantage of their abilities and allow parameters to contribute to several functions. The category of "expert" diagnostician could include highly trained technicians with access to full service manuals or computer-aided diagnostics and fully automated "artificial intelligence" based expert systems which continuously monitor a system for failures. To design for an expert diagnostician the ranking system from section 4.2 can be applied directly. As a result, the inter-relationships between the function/performance measure-parameter hierarchies could be used to speed diagnostics. An illustration of this can be seen for the system of Figure 3b; the parameter at fault can be determined simply by considering the state of the performance measures (MNPM is 1). Though the diagnosis of the system represented by Figure 3b is based on structure, to locate the failed parameter a set of rules must be applied. However, because the rules are based on structure, additional experiential knowledge, such as rules to indicate which parameter to test first, are not needed. To take advantage of this type of system, the structural hierarchy would have to be fully documented, otherwise this information would be lost and diagnosis would be very difficult. One common way this type of information is provided in service manuals is with a flow chart. The flow chart could also be automated into an expert diagnostic system to provide either computer-aided diagnostics or an automated diagnostic expert system.

### 4.4 Life Cycle Costs

In addition to the diagnostician's ability, the allowable FRU level, and the size of the system, the cost of downtime must also be considered. These factors are all included in life-cycle costs. For systems with high downtime cost each function/performance measure could be supplied by a FRU
allowing for fast diagnosis by any level diagnostician. The downtime cost and relative replacement cost of complex FRUs must be weighed against the cost of finding and replacing a less complex FRU, however. For moderate downtime costs with experts (human or computer) available, the scheme of diagnosis could take advantage of system interactions to identify failed parameters on the basis of performance measures. The result could be a system designed with a minimum number of parameters and a high level of diagnosability. The outcome would be a system with lower life-cycle costs as compared to one designed for non-expert diagnosticians. These savings would come from two specific areas. First, reducing the number of parameters the system would require to accomplish a function should reduce manufacturing costs. Second, because diagnosis time is reduced, the cost of locating failed parameters causing system failure is lowered. The cost of system downtime, failure diagnosis costs, and system manufacturing costs would need to be optimized for each individual system to create the lowest life-cycle cost system.

Another use of this analysis would be to apply the information gained to redesign one of the competing systems for improved diagnosability. This could be done using the best of parameter inter-relationships from each of the systems to create a system with the most desirable diagnosability characteristics for the intended diagnostician.

5 EVALUATION OF CONCEPTS FOR A TOOLHEAD POSITIONING SYSTEM

As an example of the use of the diagnosability evaluation methodology, this section describes the evaluation and comparison of three design concepts that accomplish the overall system function of positioning a toolhead. This system function has three major sub-functions:

1) Rapid Advance (RA): rapid movement of the toolhead to a set position
2) Feed (F): controlled movement of the toolhead to the end of travel
3) Rapid Return (RR): rapid motion of the toolhead to the starting position

These three sub-functions are assumed to be directly observable by the diagnostician. The observation or measurement of the performance of these functions constitutes a set of performance measures. We will assume the performance measures can be observed to be either good (the functionality is present) or bad (absent to some degree). It is also assumed that substantial force need be applied to allow movement of the toolhead. For the purposes of this evaluation, only solutions involving hydraulic power transmission will be considered.

Two diagnosability evaluations will be performed. The first will use connectivity information (connections between components) to determine the performance measure/parameter relationships. The second will use general functional failure modes for each component.

5.1 System Concepts

Three concepts have been developed to provide the necessary movement of the toolhead. These are shown in figures 5, 6 and 7. Figure 5 shows a system incorporating a pilot operated check valve (henceforth referred to as the POCV system). In operation, the directional control valve (A) is shifted to route flow from the pump to the head end of the cylinder (D). Directional valve (B) is shifted to direct flow to open the pilot operated check valve (E). Fluid from the rod end of the cylinder passes through (E) and (A) back to the tank. This provides for rapid advance of the toolhead attached to the end of the rod. At the end of the rapid advance phase, a cam on the rod of the cylinder contacts the normally closed limit switch, stopping electrical power to (B), allowing the valve to spring return to its normal position. This action stops pilot flow to (E), closing it. Flow from the rod end of the cylinder is forced to flow through the flow control valve (C), controlling the flow for the feed function. Excess flow is routed through the relief valve (R) back to tank. The relief valve also provides protection against excessive system pressure. For rapid return, the directional valve (A) is shifted to direct flow freely through the check valve to the rod end of the cylinder. Flow from the head end of the cylinder returns freely to the tank.
Figure 5: Pilot Operated Check Valve System

Figure 6 shows a system incorporating a deceleration valve (DECV). Operation is similar to that of the POCV system. Shifting directional valve (A) initiates rapid advance of cylinder (D), with the rod end flow returning freely to tank through the deceleration valve (B). A cam on the rod again initiates the controlled feed movement by shifting the deceleration valve to a closed position, forcing the rod end flow through the flow control valve (C). For rapid return, the directional valve (A) is shifted to direct flow freely through the check valve of (B) to the rod end of the cylinder.
Figure 6: Deceleration Valve System

Figure 7 shows a system using two separate pumps (powered by the same motor) and an unloading valve (TPUV). During rapid advance, the flow of both pumps is routed to the head end of the cylinder (D) through the directional control valve (A). A cam on the rod initiates controlled feed by shifting the unloading valve (B) to an open position. Flow from pump PY is routed directly to the tank, while flow from pump PX is routed through a flow control (C). Check valve (E) prevents flow from PX from returning directly to tank, rather excess flow from PX is routed through relief valve RX. For rapid return, the electrical supply to the limit switch is de energized, allowing the unloading valve to close, and the directional valve (A) is shifted, directing flow from both pumps to the rod end of the cylinder. Flow from the head end of the cylinder returns freely to the tank. Relief valves RX and RY provide system pressure protection.
5.2 Performance Measure-Parameter Mapping and Diagnosability Evaluation

Mapping is accomplished by determining the functions (and performance measures) related to each of the parameters. At the conceptual phase of design, "failure" may be somewhat ambiguous. If precise failure modes are known, their use will allow a more accurate evaluation. At this point in the evaluation of the toolhead positioning system, however, the parameters are assumed to be at the component level, and it is assumed that nothing is known about the operating characteristics nor the failure modes of the individual components. Therefore, connectivity between components will be used to develop the mapping by assuming that those components "downstream" of a failed component (with respect to either energy or control flow) will be affected.

For each of the systems evaluated, there are three performance measures (RA, F and RR) and a variable number of parameters that supply the related functions. For the POCV system, the parameters are related to the performance measures as follows:

1) If the motor (M) were to fail, all performance measures (RA, F, RR) would be affected.
2) If (P) were to fail, RA, F, RR would be affected
3) If (R) were to fail, RA, F, RR would be affected
4) If (A) were to fail, RA, F, RR would be affected
5) If (B) were to fail, RA, F would be affected
6) If (C) were to fail, F would be affected
7) If (D) were to fail, RA, F, RR would be affected
8) If (E) were to fail, RA, F, RR would be affected
9) If (LS) were to fail, RA, F would be affected

Several components common to all three systems have not been included to simplify the analysis, including the hydraulic tank, lines and fluid. Electric wiring and power can be assumed to be included with the A, B or LS failures. While many failures affect all three observations, it is apparent, even at this level of system abstraction, that the failure of some components will have no affect on some functions. As an example, since the flow of fluid through C (the metering valve) is only important during F (the feed function), there is no conceivable failure of C (short of a leak to the atmosphere) that would affect RA and RR.

For each of the three systems, there are seven possible failure observations. Completing the above evaluation for the other two systems, and transposing the information, each of these observations has a related set of parameters as shown in Table 2. This table provides a compact representation of the respective rule sets.

<table>
<thead>
<tr>
<th>Observation</th>
<th>Parameter Set</th>
<th>Parameter Set</th>
<th>Parameter Set</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>POCV</td>
<td>DECV</td>
<td>TPUV</td>
</tr>
<tr>
<td>RA only bad</td>
<td>(null)</td>
<td>(null)</td>
<td>(null)</td>
</tr>
<tr>
<td>F only bad</td>
<td>(C)</td>
<td>(C)</td>
<td>(null)</td>
</tr>
<tr>
<td>RR only bad</td>
<td>(null)</td>
<td>(null)</td>
<td>(null)</td>
</tr>
<tr>
<td>RA, F bad</td>
<td>(B, LS)</td>
<td>(null)</td>
<td>(null)</td>
</tr>
<tr>
<td>RA, RR bad</td>
<td>(null)</td>
<td>(null)</td>
<td>(PY, RY)</td>
</tr>
<tr>
<td>F, RR bad</td>
<td>(null)</td>
<td>(null)</td>
<td>(null)</td>
</tr>
</tbody>
</table>

Table 2: Observation/Parameter Relationships

For all three systems, the Maximum Number Of Parameter Measures (MNPM) occurs for the RA, F, RR observation. The Parameter Measure Cost (PMC) is greatest for the TPUV system (FdJ= 1 is assumed). All three systems are limited in the number of observations and hence have low values for System Interaction Complexity (SIC), resulting in relatively high values for Average Number of Parameter Measures (ANPM), especially for the TPUV system. The evaluation is summarized in Table 3.

<table>
<thead>
<tr>
<th>System</th>
<th>MNPM</th>
<th>PMC</th>
<th>SIC</th>
<th>ANPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>POCV</td>
<td>6</td>
<td>9</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>DECV</td>
<td>6</td>
<td>7</td>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>TPUV</td>
<td>8</td>
<td>11</td>
<td>2</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3: Connectivity Diagnosability Evaluation for the Toolhead Positioning System

5.3 Functional FMEA Based Diagnosability Evaluation

As the design of a system progresses, information is gained that will allow a more accurate evaluation of diagnosability. By hypothesizing generalized failure modes for each of the components in the three toolhead positioning systems, a functional Failure Modes and Effects Analysis (FMEA) can be developed, and a more meaningful comparison can be made among the systems.
Again using the POCV systems as an example, generalized failure modes can be determined for each of the components. These failure modes and their effect on the systems are detailed in Table 4. For the failure column, the letter represents the component, and the subscript the failure mode.

<table>
<thead>
<tr>
<th>Failure</th>
<th>Description</th>
<th>Observation Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>A₁</td>
<td>fail in extend</td>
<td>(RA, F)</td>
</tr>
<tr>
<td>A₂</td>
<td>fail in retract</td>
<td>(RR)</td>
</tr>
<tr>
<td>A₃</td>
<td>fail in both</td>
<td>(RA, F, RR)</td>
</tr>
<tr>
<td>B₁</td>
<td>fail to supply pressure (fail closed)</td>
<td>(RA)</td>
</tr>
<tr>
<td>B₂</td>
<td>fail to vent (fail open)</td>
<td>(F)</td>
</tr>
<tr>
<td>C₁</td>
<td>improper metering</td>
<td>(F)</td>
</tr>
<tr>
<td>D₁</td>
<td>internal leakage</td>
<td>(RA, F, RR)</td>
</tr>
<tr>
<td>E₁</td>
<td>fail open</td>
<td>(F)</td>
</tr>
<tr>
<td>E₂</td>
<td>fail closed</td>
<td>(RA, RR)</td>
</tr>
<tr>
<td>LS₁</td>
<td>fail open</td>
<td>(RA)</td>
</tr>
<tr>
<td>LS₂</td>
<td>fail closed</td>
<td>(F)</td>
</tr>
<tr>
<td>M₁</td>
<td>fail to deliver power</td>
<td>(RA, F, RR)</td>
</tr>
<tr>
<td>P₁</td>
<td>fail to deliver flow</td>
<td>(RA, F, RR)</td>
</tr>
<tr>
<td>R₁</td>
<td>fail open</td>
<td>(RA, F, RR)</td>
</tr>
<tr>
<td>R₂</td>
<td>fail closed</td>
<td>(F)</td>
</tr>
</tbody>
</table>

Table 4: FMEA for the POCV System

The results of extending the FMEA to the other systems and transposing the information are shown in Table 5.

<table>
<thead>
<tr>
<th>Observation</th>
<th>Parameter Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA only bad</td>
<td>(B₁, LS₁)</td>
</tr>
<tr>
<td>F only bad</td>
<td>(B₂, C₁, E₁, LS₂, R₂)</td>
</tr>
<tr>
<td>RR only bad</td>
<td>(A₂)</td>
</tr>
<tr>
<td>RA, F bad</td>
<td>(A₁)</td>
</tr>
<tr>
<td>RA, RR bad</td>
<td>(E₂)</td>
</tr>
<tr>
<td>F, RR bad</td>
<td>(null)</td>
</tr>
<tr>
<td>RA, F, RR bad</td>
<td>(A₃, D₁, M₁, P₁, R₁)</td>
</tr>
</tbody>
</table>

Table 5: Observation/Parameter Relationships

Evaluating as in the previous section results in a FMEA based diagnosability evaluation for the system, as shown in Table 6.

<table>
<thead>
<tr>
<th>System</th>
<th>MNPM</th>
<th>PMC</th>
<th>SIC</th>
<th>ANPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>POCV</td>
<td>5</td>
<td>15</td>
<td>6</td>
<td>2.5</td>
</tr>
<tr>
<td>DECV</td>
<td>5</td>
<td>12</td>
<td>5</td>
<td>2.4</td>
</tr>
<tr>
<td>TPUV</td>
<td>6</td>
<td>17</td>
<td>5</td>
<td>3.4</td>
</tr>
</tbody>
</table>
Table 6: FMEA Based Diagnosability Evaluation for the Toolhead Positioning System

5.4 Comparison and Discussion
The diagnosability evaluation using connectivity information, while imperfect, provides an early indication of the relative and absolute diagnosability trends of the three systems. Because of a greater number of components coupled with a relatively small set of observations, the TPUV system ranks lower than the other two systems with respect to both MNPM and ANPM. This ranking holds true in both evaluations. In the first evaluation the POCV system appears to be slightly better than the DECV system. This ranking is reversed for the second evaluation. The second evaluation should prove to be a more accurate assessment of the diagnosability of the system than the first. Subsequent evaluations, performed as the abstraction of the systems decrease, and based on physical rather than functional FMEA, should further increase in accuracy.

The evaluations provide early information on the possible placement of direct indicators to increase the diagnosability of these systems. In both evaluations (and for all three systems), the MNPM came from the (RA, F, RR) observation. The addition of an indicator(s) to distinguish between parameters for this observation would greatly increase the diagnosability of all three systems. For example, a flow meter placed just downstream of the pump would isolate M and P failures from R, A and D failures.

6 CONCLUSION
This paper has described some advances into understanding the relationship between design and diagnosis, and how that understanding can be used to increase the diagnosability of mechanical systems. Improved diagnosability in turn provides a product of higher value because of increased functionality and reduced life cycle cost.

Work has been presented to evaluate competing concepts with respect to diagnosability. The process of developing evaluation techniques has resulted in the identification of those parts of the function-form structure that most influence the ability to diagnose a mechanical system. These include independence and inter-dependence of parameter sets, and identification of parameters common to functions that can be combined as field replaceable units. Throughout this paper, the failure modes have been considered to be Boolean in nature. For non-Boolean failure modes, other techniques will need to be applied as well. These techniques include the use of Weibull Analysis, Fuzzy Sets, Markov Chains, and Influence Diagrams. In addition, the effect of one failed parameter on another was not considered, but often occurs in real systems. The techniques of design for diagnosability would remain the same and would accommodate this however.

We believe the concept of design for diagnosability cannot stand alone but must be integrated as part of the concurrent engineering design process. The savings accrued from improved diagnosability must be weighed against possible increases in other costs. The goal is to minimize the total life cycle cost. Current research focuses on further developing quantitative evaluation criteria. The procedures and techniques presented are being applied to a test bed from industry to validate their effectiveness. Future work will include investigation into the effect of reliability, availability, maintainability, and durability on diagnosability, and integration of design for diagnosability procedures with those of failure modes and effects analysis. The design for diagnosability procedures for the conceptual phase of the design process are being extended and modified for the embodiment phase of the design process. Finally, the techniques should be automated so that they become easy to use and can be incorporated into future computer aided design packages as is suggested by Will (1991) and CALS (1989).

BIBLIOGRAPHY


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