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Aircraft Fuel System Diagnostics Using Digraphs

E.M. Kelly¹ & L.M. Bartlett¹

¹ Department of Aeronautical and Automotive Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU; E-mail: E.M.Kelly@lboro.ac.uk / L.M.Bartlett@lboro.ac.uk; Tel: +44(0)1509 227276; Fax: +44(0)1509 227275

ABSTRACT

Faults within any system will decrease its functionality, with the worst case scenario being complete system failure. When faults do occur it is imperative they can be diagnosed and ultimately rectified as quickly as possible, minimising the effects of such a failure. In the case of a commercial aircraft system efficient diagnosis can optimise the time to return the aircraft to service, thus allowing less disruption to passenger travel. For a military air vehicle diagnosis of the status of the system can mean that missions can be altered or aborted given the faults detected.

With the increasing complexity of modern day systems, designed for reliability, it is usually several items that are required to fail before catastrophic or complete system failure is experienced, thus diagnosis of multiple faults is important. In addition, for the most effective diagnosis, detection needs to happen in real time. A method of finding faults or combinations of faults as they occur is the subject of this paper. The approach uses sensor readings to assess the state of the system. The method of digraphs is used to diagnose the faults by considering deviations in the sensor readings from the expected system state. Digraphs allow a means to represent the propagation of inputs through a system, reflecting the relationships and interactions between the components.

The primary research has shown the applicability of using the digraph based approach for fault diagnosis on a simulated test stand of an aircraft fuel system. The analysis has assumed steady state conditions although guidelines have been provided for use for dynamic behaviour. The technique has shown potential for extension for diagnosis to the real aircraft fuel system.

Keywords: Fault Diagnostics, Digraphs, Fuel Systems.

1.0 INTRODUCTION

Fault diagnosis has become a fundamental facet of engineering applications. Information is required about possible failures which may disrupt the running of a system and thus decrease its effectiveness. Fault diagnosis is therefore concerned with identifying and isolating the underlying causal faults leading to a
system malfunction (Papadopoulos, McDermid 2001). Further desirable characteristics incorporate both adaptability and identifying multiple faults (Venkatasubramanian, Rengaswamy et al. 2003). System processes can change due to structural alterations or external inputs. Process operating modes and conditions can also vary and so an ideal situation involves being able to adapt the scope of the diagnostics procedure. An important requirement with current complex engineering systems is the need to identify multiple faults. This can be perceived a difficult task due to the interacting nature of some faults.

Some recent approaches have used reliability assessment tools such as failure modes and effects analysis (Price 1997, Price, Taylor 1997), fault tree analysis (Hurdle, Bartlett et al. 2005) or a combination of both (Henning, Paasch 2000), as opposed to conducting diagnostics through testing techniques (Novak, Žužek et al. 2000). There has been success with diagnostics involving single faults, however multiple faults have proved more problematic with regards to generating all possible combinations of failures for larger systems.

Digraphs, also known as signed directed graphs (Palmer, Chung 2000, Vedam, Venkatasubramanian 1997), can illustrate specific fault propagations through a system. The issue surrounding diagnosing single faults in systems is addressed by Rao (Rao, N. S. V. 1993). Rao’s approach is extended (Iverson, Pattersine-Hine 1995) to also consider the combination of two failures via an AND gate. This method has potential in real-time automated monitoring and diagnosis, although its limitation lies in the number of faults revealed.

This paper applies the digraph method to a fuel rig which is representative of an aircraft fuel system. The issue of multiple faults is addressed and analysis can be carried out in real time. Section 2 provides a brief insight into digraphs through considering the modelling of the fault propagation through a system. The fuel system is presented in Section 3. Section 4 comprises a description of the procedure followed whilst developing the fuel rig digraph. System fault diagnostics based on the fuel rig digraph is conducted in Section 5 with Section 6 providing the conclusions of the research.

2.0 DIGRAPH METHOD

Digraphs (Andrews, Morgan 1986) comprise a set of nodes and edges; where the nodes (V) represent the system process variables and edges (E) the interrelationships between process variables, within an engineering application for example. The general digraph model is represented by: DG = (V,E). Examples of process variables include temperature, mass flow and pressure. A simple digraph is illustrated in Figure 1.

![Figure 1 A Simple Digraph Representation](image)

From Figure 1 it can be seen that M1 and M2, the nodes, are connected by three edges. The alphanumeric code M1 represents mass flow at location one and M2 the mass flow at location two. M1 is the independent variable whilst M2 is the dependent variable since a directed edge connects M2 to M1. The edge with a gain of +1 is a normal edge since this represents the relationship which is usually true. The second and third edges are conditional edges since their relationship is only true whenever the condition represented by ‘::’ exists. It must be noted that only one edge is true at any one time.

Process variable deviations and disturbances (Kohda, Henley 1988, Andrews, Brennan 1990) within digraphs are expressed as one of five discrete values: +10, +1, 0, -1, -10, representing respectively; large high, small
high, normal, small low and large low. An unexpected process deviation within a system is represented by ‘highlighting’ the respective node in the digraph. Subsequent propagation of the deviation through the system is represented by marking all of the nodes which were affected by the initial highlighting.

3.0 FUEL RIG SYSTEM

The purpose of a fuel system is to reliably provide an adequate amount of clean fuel at the right pressure to the engines during all phases of flight and manoeuvres. The fuel rig utilised in this research is an aircraft simulation test stand which is representative of a modern aircraft fuel system. It incorporates a stainless steel frame supporting three active supply tanks. The general layout of the fuel rig is presented in Figure 2.

![Figure 2 Fuel Rig Schematic](image)

From Figure 2 it is noticeable that the three active supply tanks; Main, Wing and Collector, each have two associated pump trays. Each tray encompasses a peristaltic pump, a pressure relief valve, powered and manual isolation valves and a pressure regulating valve. The instrumentation associated with the trays consists of a pressure switch and pressure transmitter on the transfer lines. Instrumentation for each tank comprises high and low level switches and level transmitters. Flow transmitters can also be positioned at all tank exit locations.

The main tank represents the core group of tanks on an aircraft. Two pumps, connected in parallel, pump water from the main tank to the collector tank. The auxiliary storage tanks of an aircraft fuel system are represented by the wing tank. In a similar manner to the main tank, two parallel pumps transfer water from the wing tank to the collector tank. A large single tank at the base of the fuel rig represents an aircraft engine. Fuel feeding to the engine (represented by the engine tank) is conducted via water transfer from the collector tank through a pair of parallel connected pumps. A final pump, the centrifugal refuel pump, transfers water back into the active supply tanks from the engine tank. Complete drainage of the fuel rig system is conducted through utilising the engine tank drain valve. Each of the three active supply tanks are also connected to the engine tank via a manually operated dump valve.
Two main modes of operation have been specified for the fuel rig:

1) ‘ACTIVE’: fluid is transferred from the collector tank to the ‘engine’ (engine tank). As the collector tank level decreases the transfer of water from the wing and main tanks to the collector tank commences. The tank pumps are switched on and powered isolation valves opened.

2) ‘DORMANT’: system is in standby mode, no transfer of water occurs between the active supply tanks and the engine. The tank pumps are switched off and powered isolation valves shut.

Two further modes which can be considered are ‘REFUEL’ and ‘FUEL DUMPING’. Refuelling of the fuel rig involves transferring fluid from the engine tank store to the three active supply tanks. During ‘FUEL DUMPING’ the system is drained of all fluid.

Table 1 contains all component failure modes considered in this research, which could affect the functionality of the fuel rig system. The usage of ‘***’ in the component failure mode codes represents the identification numbers for the same components illustrated in Figure 3 in Section 4.2.

<table>
<thead>
<tr>
<th>Code</th>
<th>Component Failure</th>
<th>Code</th>
<th>Component Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>TK***L</td>
<td>Tank leakage</td>
<td>TK***R</td>
<td>Tank rupture</td>
</tr>
<tr>
<td>P***L</td>
<td>Pipe leaks</td>
<td>P***B</td>
<td>Pipe blocked</td>
</tr>
<tr>
<td>P***R</td>
<td>Pipe ruptured</td>
<td>P***PB</td>
<td>Pipe partially blocked</td>
</tr>
<tr>
<td>PP***O</td>
<td>Peristaltic pump failed on / too high</td>
<td>PP***L</td>
<td>Pipe in peristaltic pump leaks</td>
</tr>
<tr>
<td>PP***S</td>
<td>Peristaltic pump failed off</td>
<td>PP***M</td>
<td>Mechanical failure of peristaltic pump</td>
</tr>
<tr>
<td>CP***O</td>
<td>Centrifugal pump failed on</td>
<td>CP***L</td>
<td>Centrifugal pump leaks</td>
</tr>
<tr>
<td>CP***S</td>
<td>Centrifugal pump failed off</td>
<td>PSV***S</td>
<td>Pressure relief valve stuck (intermed.)</td>
</tr>
<tr>
<td>PSV***C</td>
<td>Pressure relief valve closed at incorrect pressure</td>
<td>PSV***B</td>
<td>Pressure relief valve blocked</td>
</tr>
<tr>
<td>PSV***PB</td>
<td>Pressure relief valve partially blocked</td>
<td>IVP***S</td>
<td>Powered isolation valve stuck (intermed.)</td>
</tr>
<tr>
<td>IVP***B</td>
<td>Powered isolation valve blocked</td>
<td>IVP***O</td>
<td>Powered isolation valve failed open</td>
</tr>
<tr>
<td>IVP***PB</td>
<td>Powered isolation valve partially blocked</td>
<td>IVP***C</td>
<td>Powered isolation valve failed closed</td>
</tr>
<tr>
<td>CK***B</td>
<td>Check valve blocked</td>
<td>CK***PB</td>
<td>Check valve partially blocked</td>
</tr>
<tr>
<td>CK***L</td>
<td>Check valve leaks</td>
<td>BP***L</td>
<td>Pressure regulating valve leaks</td>
</tr>
<tr>
<td>BP***B</td>
<td>Pressure regulating valve blocked</td>
<td>BP***PB</td>
<td>Pressure regulating valve partially blocked</td>
</tr>
<tr>
<td>BBV***B</td>
<td>Block bleed valve blocked</td>
<td>BBV***O</td>
<td>Block bleed valve failed open</td>
</tr>
<tr>
<td>BBV***L</td>
<td>Block bleed valve leaks</td>
<td>BBV***C</td>
<td>Block bleed valve failed closed</td>
</tr>
<tr>
<td>TVT***B</td>
<td>Reconfiguration valve blocked</td>
<td>TVT***PB</td>
<td>Reconfiguration valve partially blocked</td>
</tr>
<tr>
<td>TVT***L</td>
<td>Reconfiguration valve leaks</td>
<td>TVT***P</td>
<td>Reconfiguration valve set in position</td>
</tr>
<tr>
<td>IV***O</td>
<td>Drain valve failed open</td>
<td>IV***C</td>
<td>Drain valve failed closed</td>
</tr>
<tr>
<td>IV***L</td>
<td>Drain valve leaks</td>
<td>IV***B</td>
<td>Drain valve blocked</td>
</tr>
<tr>
<td>IV***PB</td>
<td>Drain valve partially blocked</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Failure Modes

4.0 DIGRAPH DEVELOPMENT

4.1 Procedure

The procedure identified for applying digraphs to the fuel rig system follows a given format:

a) Define system to be analysed.

b) List all component failures of the system.
c) Separate the system into sub-units and components.

d) Identify and classify control loops, if present.

e) Generate the digraph models for the sub-units taking into consideration all process variable deviations which could have an effect on the variables in the model. Also consider the extent of the effect the process variable deviations may have on the system with regards to the assigning of discrete values to the deviations.

f) Form system digraph model by connecting common variables from the sub-unit models.

g) Diagnosability is conducted through a process of back-tracing from known deviating nodes within the system digraph.

A brief description covering the development of a unit digraph model is provided in Section 4.2 for the main tank section of the fuel rig. The same method is utilised to develop unit digraphs for the wing and collector tanks and transfer section. Therefore the complete fuel rig system digraph comprises all of the individual units. Due to the inclusion of partial failure modes in the analysis a further two discrete values +5 and -5, representing moderate high and moderate low, are used to describe process variable deviations and the gains associated with the edges connecting failure modes.

When developing the unit digraphs for the fuel rig four assumptions were stated:

a) The fuel rig is under complete manual control of the operator.

b) All transmitters can fail registering any one of their given readings as follows:
   - Pressure Transmitters: pressure, no pressure and partial pressure.
   - Level Transmitters: high, required level, acceptable section, low and empty.

c) Any control loops present are ‘mechanical’ not under automatic control.

d) Pressure readings are taken after pumps only.

### 4.2 Main Tank Unit Model

A detailed representation of the piping and instrumentation associated with the main tank is provided in Figure 3. The main tank unit digraph is developed through using the specific location numbers allocated to the components.

**Figure 3 Main Tank Piping and Instrumentation Diagram**
Figure 4 illustrates the unit digraph of the main tank section. The digraph was developed through a process of ‘building-up’ from the tank level node, L101. Two near identical branches extend from L101. These represent the flow of fluid from the tank through the peristaltic pumps, PP0110 and PP0120 (nodes PP110, PP120). The upper branch encompasses mass flow at 102, M102, to mass flow at 108, M108. It represents the flow of fluid through the main tank line one. The lower branch depicts flow through the main tank line two, encompassing mass flow from locations 109 to 116. Towards the end of each main tank line there is a powered isolation valve (IVP0110, IVP0120) and back pressure valve (BP0110, BP0120). If the powered isolation valves are closed by the operator then this would invoke a nullification of the relationship between the mass flows either side of the valve. The two mass flow routes from the tank, TK0110 join at node M117. Nodes M108 and M116 are connected though an ‘AND’ gate since a failure would have to occur in both main tank lines if no mass flow was to pass to the collector tank through pipes at locations 117 and 118. All of the mass flow nodes are positively dependant on the mass flow at the previous location and hence are connected by edges ‘signed’ +1. Mass flow also has a positive effect on the force powering the peristaltic pumps.

Figure 4 Main Tank Digraph

At nodes M104 and M112 ‘mechanical’ loops allow water to pass back into the tank, as illustrated by M104 – M121 – M122 – L101 and M112 – M123 – M124 – L101. The pressure relief valves (PRV) PSV0110 and
PSV0120 are represented by the relationship between nodes 121 – 122 and 123 – 124 respectively. A conditional arc between the nodes states that the relationship is only positive when the pressure in the pipes is above an amount \( P \). Six failure modes could affect the mass flow after the PRV’s.

5.0 DIGRAPH DIAGNOSTIC METHOD

The method derived for using digraphs in fault diagnosis is based on comparing system sensor readings with those which are expected whilst the system is in a known operating mode. Should a sensor(s) register a deviation(s) it would indicate that a fault has occurred within the system. Diagnosis therefore involves back-tracing through the system digraph from a specific node which represents the location of the given deviation. Back-tracing refers to the manner in which an analyst moves from a deviating node through the digraph until all possible failure modes, which could have contributed to the deviation are noted.

Only one fuel rig mode of operation is considered in the diagnostic method described in this section. The same method however, can be shown to be applicable to all modes of operation. The expected sensor readings from the fuel rig system when in the ‘ACTIVE’ state are as outlined in Table 3. The system can deviate from the ‘ACTIVE’ mode through one or more of its sensor readings, thus changing from the known operating mode to a faulty scenario. The codes used in Table 3 define the following:
- Level Transmitter (LT): RL – required level, H – high, L – low, E – empty, PSO – pumps shut off. (Collector tank readings also include three subdivisions within the acceptable section: >T1 – greater than threshold one, <T1, >T2 – less than threshold one and greater than threshold two, <T2 – less than threshold two).

<table>
<thead>
<tr>
<th>Main Tank</th>
<th>Wing Tank</th>
<th>Collector Tank</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT0110</td>
<td>FT0100</td>
<td>FT0110</td>
</tr>
<tr>
<td>RL</td>
<td>NF</td>
<td>NF</td>
</tr>
<tr>
<td>RL</td>
<td>NF</td>
<td>NF</td>
</tr>
<tr>
<td>&gt;PSO</td>
<td>NF</td>
<td>F</td>
</tr>
<tr>
<td>PSO</td>
<td>NF</td>
<td>NF</td>
</tr>
</tbody>
</table>

Table 3 ACTIVE Mode Sensor Readings

During the diagnostics procedure information is used from the sensor readings to ‘flag’ nodes, and sometimes whole digraph sections, representing process variables which are known to be not deviating from the system operating mode. ‘Flagged’ sections therefore indicate the absence of a failure. Back-tracing from a known deviating node ceases once the analyst reaches a flagged section. The failure modes which may have attributed to the process variable deviation(s) are determined through back-tracing.

The following assumptions were employed during the investigation to determine which fault(s) could lead to a specific deviation:
- a) All transmitters provide reliable readings.
- b) If back-tracing and hit ‘0’ signed arc, it must be stated that the failure modes after the arc could only contribute to the sensor deviation if the condition required for the ‘+1’ signed arc is met.
- c) Three flow states are considered in the analysis. For full flow and no flow failures, after the tank pumps, a fault must have occurred in both tank feed lines before the ‘AND’ gate in the digraph. For partial flow failures, of gains ±5 and -1, a failure must have occurred in one of the tank lines.
d) All back-tracing ceases at the tank level node when considering individual transmitter readings, provided there are no ‘flagged’ sections between the transmitter and level node.

5.1 Application of Diagnostic Method to Registered Sensor Deviations

A single faulty fuel rig scenario, reference Table 4, is used to illustrate the diagnostic capability of the fuel rig digraphs. The scenario deviates from the known operating mode of the system (ACTIVE), as indicated by the bold type face. Only main tank deviations are discussed in detail as a means of correlating between the diagnostic results retrieved through back-tracing and the main tank unit digraph illustrated in Figure 4.

Table 4 Faulty Scenario Sensor Readings

The diagnostic results obtained from the digraph are thus expanded:
1) From the obtained readings it is noticed that FT0110 and PT0120 both register a deviation. Since ‘normal’ pressure is registered at PT0110 it can be deduced that the partial flow has resulted from a failure in the main tank feed line two.
2) The failure modes sought are therefore those relating to ‘no flow’ from the lower branch of the main tank unit digraph. Thus, back-tracing beyond the ‘AND’ gate takes into consideration failure modes resulting in a large negative disturbance e.g. M116(-10); the large negative disturbance correlates with the situation of ‘no flow’.
3) From the non-deviating transmitter readings obtained, the following parts of the digraph can be flagged: upper branch incorporating PT0110 and the sections related to the level transmitter LT0110 and flow transmitter FT0110.
4) Firstly node PFT110 is addressed since it is at this location that the deviating flow transmitter reading is registered. It is assumed that the sensors are reliable and so the direct failure mode FT110PF is disregarded. Following the fault propagation to node M117 leads to the failure mode of pipe 117 being partially blocked, P117PB.
5) Back-tracing past the ‘AND’ gate on the lower branch reveals failures leading to M116(-10). There are four failure modes which could lead to a large negative disturbance at node M116; pipe 116 being blocked or ruptured (P116B/R) and the block bleed valve BP0120 failing either closed or blocked (BP120C, BP120B). Further failure modes are determined through following the fault propagation from node M115(-10) to the tank level node L101.
6) With regards to the pressure transmitter deviation node PPT120 is addressed. Back-tracing from node PPT120 takes into account failure modes leading to a large negative disturbance (-10), so representing the deviation of ‘no pressure’. In a similar manner to the failure mode FT110PF, PT120PP is ignored since it is assumed that the sensor readings are reliable. The fault propagation is followed to node M131 leading to the failure modes pipe 131 blocked or ruptured (P131B/R). Further failure modes are determined through following the fault propagation from M130(-10) through to node L101.

The diagnostic results reached through the process of back-tracing for the two deviations in scenario one are shown in Table 5. The failure mode codes correlate with those highlighted in Section 3.2.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>LT0110</th>
<th>FT0100</th>
<th>FT0110</th>
<th>PT0110</th>
<th>PT0120</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (ACTIVE)</td>
<td>NF</td>
<td>PF</td>
<td>P</td>
<td>NP</td>
<td></td>
</tr>
</tbody>
</table>

Table 5 Faulty Scenario Diagnostic Results


AND

For the given scenario it is possible that either a single fault or multiple fault may have led to the registered deviations; the diagnostic results confirm this. In total there are 374 failure mode options; 11 single order and 363 second order. Final human intervention, with the ability to call on engineering knowledge and experience will target the most probable failure modes. The list of failure modes can be further reduced by changing the operating mode of the system and comparing the causes for any registered sensor deviations noted in the two phases. In the case of multiple deviating sensors, the diagnostic results for each sensor are AND-ed together to determine possible failure mode options. By AND-ing the diagnostic results in Table 5 some of the single faults leading to the deviation can be determined: Pipe 109 blocked (P109B) or peristaltic pump PP0120 failed shut off (PP120S). Potential multiple faults could be powered isolation valve IVP0120 closed and block bleed valve BBV0120 blocked (IVP120C.BBV120B) or pipe 109 ruptured and back pressure valve BP0120 blocked (P109R.BP120B).

Through incorporating ‘flagging’ into the diagnostics process potential inconsistent failure mode results and anomalies are removed. This acts as a form of consistency check and removes the possibility for conflicting results to exist between non-deviating sensor readings and failure modes ascertained through back-tracing from deviating nodes. There are multiple possible failure modes which may have occurred giving rise to the registered transmitter deviations. Since there is no hierarchy involved with the failure modes it is assumed that they all have the same probability of occurrence.

6.0 CONCLUSION

Digraphs provide a clear representation of the relationships between system variables; both input and output as they closely reflect the physical structure of a system. It is these characteristics which make digraphs suited to illustrating fault propagation. Fault propagation is depicted through both direct and indirect influences of a faulty component. Possible faulty components are determined through a process of back-tracing from a node registering a known deviation. System digraph development requires a thorough understanding of the fundamental system function and individual components, it does not require a complete quantitative description. Digraphs can therefore be developed from information regarding the structure of system equations, data surrounding the system operating modes and detailed engineering drawings.

The results from the application of the digraph method to the diagnostics of the fuel rig are credible. Valid failure mode results are obtained when considering single or multiple faults in either individual sections of the fuel rig or across the fuel rig system as a whole. In some cases many fault options are yielded for a given deviation. Extending the diagnostic method to take into account system transient effects requires real-time information as to the status of the fuel rig tank levels; more specifically the rate of change in height, $\frac{\delta h}{\delta t}$. This can be used in conjunction with the transmitter readings and data regarding previous failures to identify possible faults. This could be further aided through the inclusion of other sensors placed in different locations from those already used.

It is proposed that future research investigate the addition of flow sensors at other locations in the fuel rig and in turn deduce optimum sensor positioning from the diagnostic results. As a means of honing in on the most probable results, failure modes for a given deviation could be weighted and therefore, for the cases where there are multiple options, it would be possible to highlight the most likely fault(s). A final consideration which could broaden the analysis would involve assuming that flow only exists in tank line one and that in the event of a failure in line one flow in tank line two would be induced. This would in turn introduce the concept of ‘modelling’ redundancy within systems with digraphs.
7.0 REFERENCES


Acknowledgements
The authors wish to thank the SEIC, BAE Systems for allowing the use of the fuel rig in this analysis.