Application of the Digraph Method in System Fault Diagnostics

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Application of the Digraph Method in System Fault Diagnostics

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Overview

- Fault diagnosis is an important facet of engineering applications.
- Introduce the application of the digraph method to determine the likely causes leading to a system malfunction.
- A description of digraphs and their application in fault diagnostics is provided.
- A simple example is used for demonstration purposes.
Introduction to Digraphs

- Qualitative causal model which illustrates the cause and effect behaviour in a system.

- Digraphs comprise:
  i. Set of nodes, representing system process variables.
  ii. Nodes are connected by edges (lines) illustrating the inter-relationships which exist between process variables.
Examples of process variables include:

- Mass flow.
- Pressure.
- Signals from sensors.
- Temperature.

Process variable deviations are represented through one of five discrete values:

- +10/-10: large high / large low.
- +1/-1: moderate high / moderate low.
- 0: normal.
An Example of a Simple Digraph

- M1: mass flow at location 1 - independent variable.
- M2: mass flow at location 2 - dependant variable.
- Two arcs:
  - ‘+1’ signed - normal.
  - ‘0: V1 closed’ signed - conditional.
Digraph Development

1) Define system to be analysed.

2) Compile list of system component failures.

3) Separate system into sub-units.

4) Identify control loops, if present.

5) Generate digraph models for the sub-units.

6) Form system digraph by connecting any common variables from the sub-unit models.
The Water Tank System

- Three valves: V1, V2, V3.
- Two level sensors: S1, S2.
- Two control units: C1, C2.
- Six pipe sections: P1, P2, P6, P7, P8, P9.
The Water Tank System

- System information obtained from the flow sensors, VF1-3 and tray sensor, SP1.
- Flow sensors detect flow or no flow.
- Tray sensor detects presence or absence of water.
- Two operating modes are specified.

<table>
<thead>
<tr>
<th>Operating Mode</th>
<th>VF1</th>
<th>VF2</th>
<th>VF3</th>
<th>SP1</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACTIVE</td>
<td>Flow</td>
<td>Flow</td>
<td>No Flow</td>
<td>No Water</td>
</tr>
<tr>
<td>DORMANT</td>
<td>No Flow</td>
<td>No Flow</td>
<td>No Flow</td>
<td>No Water</td>
</tr>
</tbody>
</table>
- Sixteen scenarios developed from the potential sensor readings.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>VF1</th>
<th>VF2</th>
<th>VF3</th>
<th>SP1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>W</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>NW</td>
</tr>
<tr>
<td>3</td>
<td>NF</td>
<td>F</td>
<td>F</td>
<td>W</td>
</tr>
<tr>
<td>4</td>
<td>NF</td>
<td>F</td>
<td>F</td>
<td>NW</td>
</tr>
<tr>
<td>5</td>
<td>NF</td>
<td>NF</td>
<td>F</td>
<td>W</td>
</tr>
<tr>
<td>6</td>
<td>NF</td>
<td>NF</td>
<td>F</td>
<td>NW</td>
</tr>
<tr>
<td>7</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
<td>W</td>
</tr>
<tr>
<td>8</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
<td>NW</td>
</tr>
<tr>
<td>9</td>
<td>F</td>
<td>F</td>
<td>NF</td>
<td>F</td>
</tr>
<tr>
<td>10</td>
<td>F</td>
<td>F</td>
<td>NF</td>
<td>F</td>
</tr>
<tr>
<td>11</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>NF</td>
</tr>
<tr>
<td>12</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>NF</td>
</tr>
<tr>
<td>13</td>
<td>NF</td>
<td>F</td>
<td>F</td>
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<td>14</td>
<td>NF</td>
<td>F</td>
<td>NF</td>
<td>NF</td>
</tr>
<tr>
<td>15</td>
<td>F</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
</tr>
<tr>
<td>16</td>
<td>F</td>
<td>NF</td>
<td>NF</td>
<td>NW</td>
</tr>
</tbody>
</table>
## Component Failure Modes

- Failure modes considered which could affect the functionality of the water tank system.

<table>
<thead>
<tr>
<th>Code</th>
<th>Component Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>PiB(1-2, 3-4, 5-6)</td>
<td>Pipe Pi is blocked</td>
</tr>
<tr>
<td>ViFC(1 ≤ i ≥3)</td>
<td>Valve Vi fails closed</td>
</tr>
<tr>
<td>CiFH (1 ≤ i ≥2)</td>
<td>Controller Ci fails high</td>
</tr>
<tr>
<td>SiFH (1 ≤ i ≥2)</td>
<td>Sensor Si fails high</td>
</tr>
<tr>
<td>TR</td>
<td>Water tank ruptured</td>
</tr>
<tr>
<td>NMWS</td>
<td>No mains water supply</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Code</th>
<th>Component Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>PiR(1-2, 3-4, 5-6)</td>
<td>Pipe Pi is ruptured</td>
</tr>
<tr>
<td>ViFO(1 ≤ i ≥3)</td>
<td>Valve Vi fails open</td>
</tr>
<tr>
<td>CiFL (1 ≤ i ≥2)</td>
<td>Controller Ci fails low</td>
</tr>
<tr>
<td>SiFL (1 ≤ i ≥2)</td>
<td>Sensor Si fails low</td>
</tr>
<tr>
<td>TL</td>
<td>Water tank leaks</td>
</tr>
<tr>
<td>WOST</td>
<td>Water in overspill-tray</td>
</tr>
</tbody>
</table>
Three assumptions:

i. Given a pipe rupture, flow sensor registers no flow.

ii. Tank rupture volume loss >> tank leakage.

iii. System is in steady state.

Unit digraph models developed for the three water tank valves.

Each unit digraph considers:

- Component functions.
- Effects of failure modes.
Water Tank System Unit Digraphs
Water Tank System Digraph
Diagnostics is based on comparing retrieved sensor readings with those expected.

Given the presence of a deviation, diagnosis involves:
- Noting the location of the given deviation.
- Determine the component failure modes which may have contributed to the deviation.

Fault diagnosis is conducted through a process of back-tracing.
Deviation noted after valve. Expect flow, no flow registered.
Commence back-tracing from noted large, negative disturbance:
- M2(-10) → P2B.
- M2(-10) → M1(-10) → P1B.
Two methods considered:

1) Analyst is required to fully back-trace through the digraph until a point is reached where no further back-tracing can be conducted.

2) Non-deviating sections are flagged. Back-tracing from a deviating node ceases once a flagged section is reached.
Diagnostics of a Faulty Scenario

- Example used to demonstrate diagnostic capability of water tank system digraph.

- Water tank assumed to be in the ACTIVE mode.

- Sensor readings retrieved reveal scenario ‘FS16’.

<table>
<thead>
<tr>
<th>Operating Mode</th>
<th>VF1</th>
<th>VF2</th>
<th>VF3</th>
<th>SP1</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACTIVE</td>
<td>Flow</td>
<td>Flow</td>
<td>No Flow</td>
<td>No Water</td>
</tr>
<tr>
<td>‘FS16’</td>
<td>Flow</td>
<td>No Flow</td>
<td>No Flow</td>
<td>No Water</td>
</tr>
</tbody>
</table>
Fault Diagnostics of ‘FS16’

- Deviation only noted by VF2, flag sections of system digraph incorporating:
  - V1 and control loop one.
  - V3 and control loop two.
  - Overspill tray.
Fault Diagnostics of ‘FS16’

- Node M7 addressed – represents status of mass flow exiting V2.
- M7 is ‘marked’ on the system digraph.
- Determine the failure modes leading to large negative disturbance i.e. -10.
- -10 represents registered ‘no flow’ status.
- Back-tracing commences from M7(-10); reveals five component failure modes.
Fault Diagnostics of ‘FS16’

- $M7(-10) \rightarrow V2FC, P7B, P7R.$
- $M7(-10) \rightarrow M6(-10) \rightarrow P6B, P6R.$
- $M7(-10) \rightarrow M6(-10) \rightarrow L4(-10)$, back-tracing ceases.
- Five component failure mode results: Valve 2 failed closed, Pipe 7 blocked or ruptured, Pipe 6 blocked or ruptured.
Conclusions

- Component failure mode results are consistent with recorded sensor readings.

- Flagging of non-deviating sections removes conflicting results, also reduces number of determined fault combinations.

- Method 2 advised method since results displaying inconsistencies between sensor readings are removed.

- Digraph suitable method for steady state analysis.
Future Research

- Implications for dynamic behaviour – preliminary results are positive.
- Investigation into computational optimisation of back-tracing enabling real-time analysis.
- Scalability – it is necessary to apply method to larger, more complex, system to ensure industrial validity.
Summary

- Digraphs clearly illustrate the information flow in a cause-effect relationship.

- Closely reflect the physical structure of the system under investigation.

- Conduct diagnostics through back-tracing from a known deviation \( \rightarrow \) introduce flagging of non-deviating sections.

- Valid diagnostic results determined for steady state.
Thank you for your attention.

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