Diagnosing faults in systems using a fault tree based model

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Diagnosing Faults in Systems Using a Fault Tree Based Method

E. E. Hurdle, L. M. Bartlett, J. D. Andrews
Aeronautical and Automotive Engineering, Loughborough University, Loughborough, UK

Abstract
Advances in technology have brought about increased system complexity, therefore making fault diagnosis and rectification in systems a more difficult task to perform. However well a system is maintained, at some point it will encounter component failures. This will result in a reduction in system performance or worse still increased down-time from operation. A number of components could fail simultaneously changing the symptoms exhibited by the faults individually, which may further increase the time taken to obtain a successful diagnosis.

In the event of a failure, to lessen the impact on a system it is important that the cause is diagnosed as soon as possible. Once a diagnosis has been made the problem can be rectified either by repairing or replacing the component, returning the system to normal operation. Fast diagnosis and rectification in aircraft systems reduces the time taken for planes to be returned to service. In the case of autonomous robotic vehicles, diagnosis of faults can aid the completion of successful missions.

This paper presents a method for diagnosing faults when potentially multiple failures have occurred. The status of the system is acquired from a series of sensor readings. Diagnosis is obtained by taking into consideration the system dynamics and comparing actual system behaviour to that expected in order to highlight any sensor readings indicating unusual behaviour. Potential causes of these readings are described using fault trees. Non-coherent fault trees, which consider both component failed and working states, are used in the investigation to obtain a diagnosis. The requirements of the dynamical method are demonstrated using an example fluid system.

Keywords: Fault diagnosis, fault tree analysis, fault detection

1. Introduction
The increased complexity of modern day systems has made the diagnosis of faults a more difficult process. When a failure occurs in a system it is important that the fault is detected and rectified as quickly as possible in order to ensure minimal effects are encountered. Fault diagnosis can be performed in two different ways. The first involves testing the system for faults at specific points in time. A second approach continuously monitors a system in order to detect faults as and when they occur.

A number of methods have been developed that test systems for faults at specified points in time. Novak *et al* [1-4] developed a sequential fault diagnostic tool that carries out a series of tests to determine the status of the system. The method uses symptoms of the system behaviour to determine the most likely cause of failure. The sequential fault diagnostic tool determines which tests are used and the order in which they are carried out to ensure that the fault is obtained as efficiently as possible. Pattipati *et al* [5] used a similar approach using heuristic search algorithms to obtain the quickest possible diagnosis. Both these methods do not take into consideration the possibility of multiple failures existing at any

point in time. Sequential test sequencing was extended to include multiple failures by Shakeri *et al* [6] but takes a long time to obtain a diagnosis. Research carried out by Paasch and Mocko [7] used Failure Modes and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) to diagnose faults in systems, again only considering single failures. A method devised by Price [8] uses FMEA to diagnose multiple faults in systems. However, failures were only generated to a certain likelihood of occurrence, therefore some failures may not become apparent in the analysis.

A method that provides continuous on-line monitoring and rectification of systems using statecharts and fault trees has been developed by Papadoupolos [9]. The fault trees only contain component failures and not the working states. As a result some faults occurring simultaneously have exhibited conflicting rectification procedures. A fault tree based method only considering component failures was devised by Yangping [10] to continuously monitor a nuclear power plant for faults using genetic algorithms. This was found to be slow in obtaining failures.

System failure can be the result of more than one fault occurring in the same time frame. This paper presents a fault tree based method for diagnosing multiple faults in systems. The approach has already been applied to a system in steady state that has yielded credible results [12]. The status of the system is obtained from sensor readings. Potential causes of these readings are described using fault trees. A failure is diagnosed by taking into consideration system dynamics and by comparing actual sensor readings to expected model behaviour. The method described in this paper is applied to a simple water tank level control system to demonstrate its features.

2. The Generalised Method

The method for diagnosing faults in system can be generalised into the following points:

- Obtain readings for each sensor in the system and calculate parameters.
- Develop non-coherent fault trees for each sensor reading.
- Compare the monitored parameters for the different sensors where possible. This can be direct comparison or using some readings to calculate what others should read. In the case where parameters do not agree it indicates that these sensors have failed. If all parameters from the sensor readings disagree then all sensors will be deemed unreliable and the analysis would be based on those readings that cannot be checked.
- Obtain the model behaviour of the system in order to identify how the system should be behaving at any given point in time depending on the operating mode.
- Construct a top event structure from the sensor readings that have deviated from that expected for the operating mode. Combine all readings using an AND gate.
- Perform analysis to obtain potential causes of failure.
- As only failed components need to be considered remove any working states from the potential causes of failure in the list to give a coherent approximation.
- Check the potential causes of system failure obtained from the analysis against the sensors reading true to the operating mode and for the given parameters. Any potential causes of failure that could cause these sensor readings can be removed from the list.
- If there is more than one possible potential cause of failure remaining use importance measures to determine the most likely outcome. The importance measure used in the analysis is based on the Fussell-Veseley probabilistic measure

of minimal cut set importance, [11]. This measure of importance I_{C_i} is defined as the probability of the occurrence of minimal cut set *i* given that the system has failed and is shown in Equation 1,

$$I_{C_i} = \frac{P(C_i)}{Q(\mathrm{q}(t))}, \quad (1)$$

where, $P(C_i)$ is the probability of a potential cause of failure *i* occurring and $Q(\mathbf{q}(t))$ is the probability of failure in a given scenario.

3. The Simple Water Tank System

The simple water tank system used to illustrate the method is shown in Figure 1. The main objective is to keep the level of water in the tank between upper and lower set limits. When the system contains no failures and is in an operational mode water will flow out of the tank through the outlet valve V2. Water flowing from the tank is replaced by the level control system, which opens the inlet valve V1 in order to refill the tank up to the required level, [12]. If the amount of water in the tank reaches an undesired level the control system will open the safety outlet valve V3 allowing the water an alternative route out of the tank. An overspill tray is situated underneath the tank to collect any water in the event of a leakage, rupture or tank overflow.

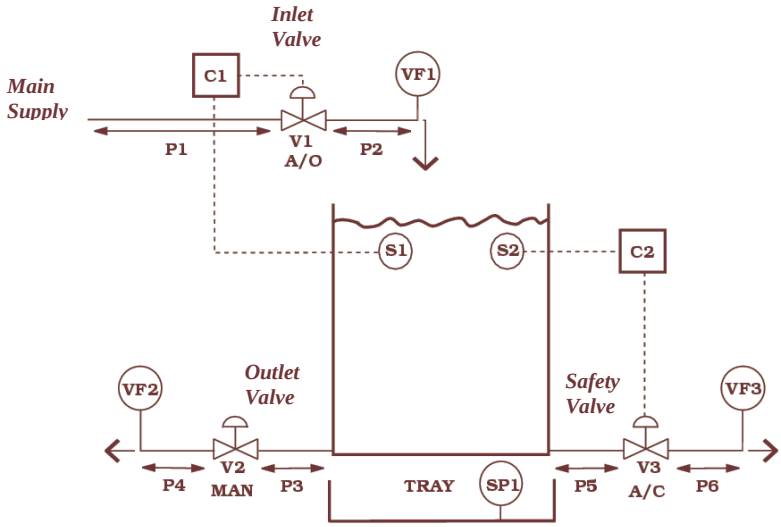

Figure 1: Simple Water Tank System

3.1 System Components

The system contains three valves, labelled V1, V2 and V3 in Figure 1. There are also two level sensors S1 and S2, two controllers C1 and C2, six pipes P1 to P6 and the overspill tray TRAY.

V1 is an air-to-open (A/O) inlet valve that allows water to flow into the tank. This is controlled by C1. If the system contains no failures whilst active and the level of water in the tank indicated by sensor S1 drops below that required, C1 will open V1 in order to refill the tank. C1 would then close V1 once the required level has been reached. The second valve listed, V2 is manually operated (MAN). It can be opened and closed when water is required from the system.

The final valve V3 is an air-to-close safety valve (A/C) used when the level of water in the tank becomes too high. If S2 were to detect a very high level of water in the tank then C2 would open V3. The overspill tray is used to identify if water is being lost from the system

through a leakage, rupture or if the tank overflows. A failure will have occurred somewhere in the system if water is present in the tray.

3.2 System Operation Assumptions

A number of assumptions have been made regarding the operation of the system:

- The system always starts off with the adequate (normal) level of water in the tank.
- In the normal operational mode it can be assumed that the flow rate into the tank through V1 has the capability to be greater than flow out at V2 (which varies depending on the height of water in the tank). Therefore the required water level in the tank can always be maintained when water is being drawn out of the system in this way.
- The areas of pipes P5 and P6 are twice that of the other pipes in the system so that water can be drained quickly from the tank in the event of the level rising too high. Flow out of V3 is therefore greater than flow in at V1.
- When a 'rupture' occurs in the tank this indicates that the liquid flow through the rupture will be greater than the maximum flow into the tank through valve V1. Therefore replenishment is not possible.
- Maximum flow into the tank through valve V1 will be greater than flow out through a 'leak' in the system. If a leak occurs along side V2 being open then flow out of the system will be greater than flow in.
- Initial conditions have the water level as normal.

3.3 Dynamic System Operating Modes

3.3.1 Sensor Locations, Rate of Change and Height

The flow in and out of the system is observed using three flow sensors, located next to each valve. The sensors are denoted by VF1, VF2 and VF3 for the locations at V1, V2 and V3 respectively. Each of these sensors can measure the actual flow rate in the system, indicated by a discrete value if there is flow (F), or no flow (NF), at their particular location in the system. A final sensor denoted SP1 is located in the overspill tray to show water presence. This sensor can indicate if there is water (W) or no water (NW), and can also give an actual measurement of water in the tray. These sensor locations are called the system observation points.

In this study a scenario refers to a set of observations (sensor readings) that occur at a point in time. For the tank system additional information can be used to determine the presence of faults and help identify potential causes, these being, height of water h and rate of change $\dot{h}$ that can be calculated from the flows in and out of the system. The height of water in the tank is considered in discrete categories: empty (E), low (L), normal (N), high (H), very high (VH) or full (F). Not all rates of change are valid for each scenario, as this will depend upon the flows in and out of the system. For example, in the situation where there is no flow into the system and flow out the rate of change can only be decreasing. Considering the physical system in this way will reduce the set of conditions on h and $\dot{h}$ that need to be considered for each set of sensor readings.

Level sensors S1 and S2 in the simple water tank system are also used in the system analysis in order to indirectly determine the behaviour of the other components in the system. Each level sensor records the level of water in the tank and the rate of change of height at any point in time. These parameters can also be obtained from calculations using the readings from the volume flow rate and spill tray sensors. The height indicated by the

level sensors is categorised in the same way as the height from the flow rate and spill tray readings.

A comparison is made of the level and the rate of change values produced using the three possible approaches (2 sensors, 1 calculated). If all are in agreement then it indicates that all the sensors are showing reliable readings. A fault tree can represent potential causes of system failure with a top event structure using information from all sensor readings. In the case of one level or rate of change disagreeing with the other two, information provided by the unreliable source is ignored when tracing the potential system faults. All sensor readings would be deemed unreliable in the event where none agree and the analysis would be be based only on those sensor readings that cannot be checked.

From the observation points at VF1, VF2, VF3 and SP1, there are sixteen scenarios that could potentially occur. Table 1 lists the possible system scenarios that can be identified from the system observation points, along with the possible heights and rates of change for the level sensor readings for these scenarios when all readings are reliable.

Scenario	VF1	VF2	VF3	SP1	HEIGHT	RATE	S1/S2 HEIGHT	S1/S2 RATE
1	F	F	F	W	h = L, N, H, VH, F	$\dot{h} < 0$	h = L, N, H, VH, F	$\dot{h} < 0$
2	F	F	F	NW	h = L, N, H, VH, F	$\dot{h} < 0$	h = L, N, H, VH, F	$\dot{h} < 0$
3	F	F	NF	W	h = L, N, H, VH, F	$\dot{h} < 0$	h = L, N, H, VH, F	$\dot{h} < 0$
4	F	F	NF	NW	h = L, N, H, VH, F	$\dot{h} > 0$	h = L, N, H, VH, F	$\dot{h} < 0$
5	F	NF	F	W	h = L, N, H, VH, F	$\dot{h} < 0$	h = L, N, H, VH, F	$\dot{h} < 0$
6	F	NF	F	NW	h = L, N, H, VH, F	$\dot{h} < 0$	h = L, N, H, VH, F	$\dot{h} < 0$
7	F	NF	NF	W	h = L, N, H, VH, F	$\dot{h} < 0$	h = L, N, H, VH, F	$\dot{h} < 0$
	F	NF	NF	W	h = E	$\dot{h} = 0$	h = E	$\dot{h} = 0$
	F	NF	NF	W	h = E, L, N, H, VH, F	$\dot{h} > 0$	h = E, L, N, H, VH, F	$\dot{h} > 0$
8	F	NF	NF	NW	h = E, L, N, H, VH, F	$\dot{h} > 0$	h = E, L, N, H, VH, F	$\dot{h} > 0$
9	NF	F	F	W	h = L, N, H, VH, F	$\dot{h} < 0$	h = L, N, H, VH, F	$\dot{h} < 0$
10	NF	F	F	NW	h = L, N, H, VH, F	$\dot{h} < 0$	h = L, N, H, VH, F	$\dot{h} < 0$
11	NF	F	NF	W	h = L, N, H, VH, F	$\dot{h} < 0$	h = L, N, H, VH, F	$\dot{h} < 0$
12	NF	F	NF	NW	h = L, N, H, VH, F	$\dot{h} < 0$	h = L, N, H, VH, F	$\dot{h} < 0$
13	NF	NF	F	W	h = L, N, H, VH, F	$\dot{h} < 0$	h = L, N, H, VH, F	$\dot{h} < 0$
14	NF	NF	F	NW	h = L, N, H, VH, F	$\dot{h} < 0$	h = L, N, H, VH, F	$\dot{h} < 0$
15	NF	NF	NF	W	h = L, N, H, VH, F	$\dot{h} < 0$	h = L, N, H, VH, F	$\dot{h} < 0$
	NF	NF	NF	W	h = E	$\dot{h} = 0$	h = E	$\dot{h} = 0$
16	NF	NF	NF	NW	h = E, L, N, H, VH, F	$\dot{h} = 0$	h = E, L, N, H, VH, F	$\dot{h} = 0$

Table 1: System Scenarios, Possible Heights and Rates of Change

3.3.2 ACTIVE and DORMANT Operating Modes

The water tank system has two modes of operation, these being ACTIVE and DORMANT. The expected sensor readings and rates of change are dependent upon the system operating mode and the level of water in the tank at a given point in time. These are listed in Table 2 for the ACTIVE and DORMANT modes respectively. The expected system behaviour can be used to indicate for any given operating mode and level of water in the tank if a deviation has occurred.

The system aims to maintain the level of water in the tank at ‘normal’. However, the level could be any value. If the level of water in the tank is ‘normal’ or ‘high’ and the system is ACTIVE then water is being drawn out through valve V2 and there should be no water coming into the tank through V1. Water would not exit the tank through V3 and there would be no water in the overspill tray. Therefore the sensor readings exhibited should be the same as those in scenario 12 with decreasing rate of change (shown in Table 2). If the level of water drops to ‘low’ or ‘empty’ then valve V1 would open allowing the tank to be refilled. Therefore the sensor readings in this case should be as those listed in scenario 4, in Table 1. If the level of water in the tank is ‘very high’ or ‘full’ and the system is ACTIVE then for normal operation to occur there should be no flow into the tank at valve V1, flow at both V2 and V3 and no water in the overspill tray, as given in scenario 10, with a decreasing rate of change.

Mode	HEIGHT	Scenario	V1	V2	V3	TRAY	RATE
ACTIVE	E	4	F	F	NF	NW	$\dot{h} > 0$
ACTIVE	L	4	F	F	NF	NW	$\dot{h} > 0$
ACTIVE	N	12	NF	F	NF	NW	$\dot{h} < 0$
ACTIVE	H	12	NF	F	NF	NW	$\dot{h} < 0$
ACTIVE	VH	10	NF	F	F	NW	$\dot{h} < 0$
ACTIVE	F	10	NF	F	F	NW	$\dot{h} < 0$
DORMANT	E	8	F	NF	NF	NW	$\dot{h} > 0$
DORMANT	L	8	F	NF	NF	NW	$\dot{h} > 0$
DORMANT	N	16	NF	NF	NF	NW	$\dot{h} = 0$
DORMANT	H	16	NF	NF	NF	NW	$\dot{h} = 0$
DORMANT	VH	14	NF	NF	F	NW	$\dot{h} < 0$
DORMANT	F	14	NF	NF	F	NW	$\dot{h} < 0$

Table 2: Expected sensor readings and rates of change for each height of water in the tank for the ACTIVE and DORMANT operating modes

In the DORMANT operating mode water is not being drawn from valve V2. If the level of water in the tank is ‘normal’ or ‘high’ then all three valves remain closed. No water present in the overspill tray would indicate that the sensor readings are as those given in scenario 16, with a zero rate of change. If an ‘empty’ or ‘low’ level occurs in the DORMANT operating mode then V1 will open to try and refill the tank up to ‘normal’. In this case, assuming there is no flow at V2 and V3, and no water in the overspill tray the sensor readings exhibited would be as those in scenario 8. Finally, if the level in the tank is ‘very high’ or ‘full’, V3 will open to try and reduce the level of water in the tank. Sensor readings exhibited in this case would be the same as in scenario 14.

3.3.3 Component Potential Causes of Failure

Table 3 lists the failure modes and the abbreviation code used for each component for the simple water tank system. The two operating modes are also represented in the fault trees. ACTIVE signifies the operator has attempted to open valve V2. DORMANT is used to indicate that the operator has tried to close V2. It should be noted that this is a two mode system and so only one of the variables ACTIVE or DORMANT can be true at any time.

Code		Component Failure	Code		Component Failure
P_iB $(1 \le i \le 6)$	-	Pipe P_i is Blocked	S_iFL $(1 \le i \le 2)$	-	Sensor S_i Fails Low
P_iF $(1 \le i \le 6)$	-	Pipe P_i is Fractured	S_iFE $(1 \le i \le 2)$	-	Sensor S_i Fails Empty
V_iFC $(1 \le i \le 3)$	-	Valve V_i Fails Closed	C_iFH $(1 \le i \le 2)$	-	Controller C_i Fails High
V_iFO $(1 \le i \le 3)$	-	Valve V_i Fails Open	C_iFL $(1 \le i \le 2)$	-	Controller C_i Fails Low
S_iFF $(1 \le i \le 2)$	-	Sensor S_i Fails Full	TR	-	Water Tank Ruptured
S_iFVH $(1 \le i \le 2)$	-	Sensor S_i Fails Very High	TL	-	Water Tank Leaks
S_iFH $(1 \le i \le 2)$	-	Sensor S_i Fails High	NWMS	-	No Water from the Main
S_iFN $(1 \le i \le 2)$	-	Sensor S_i Fails Normal			Supply

Table 3: Potential Component Failures

4. Sensor Models

4.1 Fault Tree Construction

In order to apply the fault tree based method to the water tank system failure logic diagrams describing the causes of all possible flow rate and spill tray sensor readings are created. These are developed in a fault tree in terms of the component failure and working conditions, the system operating state, rate of change and height of water in the tank. The possible sensor readings for the volume flow rate and overspill tray sensors in the system are listed in Table 4.

Abbreviation		Sensor Readings	Abbreviation		Sensor Readings
FTV1	-	Flow Through Valve V1	NFTV2	-	No Flow Through Valve V2
FTV2	-	Flow Through Valve V2	NFTV3	-	No Flow Through Valve V3
FTV3	-	Flow Through Valve V3	WOST	-	Water in the Overspill Tray
NFTV1	-	No Flow Through Valve V1	NWOST	-	No Water in the Overspill Tray

Table 4: Sensor Readings

Fault trees are drawn to describe the causes of the events listed in Table 4, and also for the possible readings from the level sensors S1 and S2. Non-coherent fault trees were generated for each of the flow rate and spill tray sensor readings listed in Table 4. These consider both working and failed states and are constructed using AND, OR and NOT logic. Fault trees were also drawn for readings from the level sensors S1 and S2.

4.2 System Fault Detection Including Dynamics

To find all the potential causes of system failure, a top event structure is constructed from the information that is provided by the observation points and the level sensor readings in the system. This is now demonstrated when considering the system in the DORMANT operating mode. Consider inducing the failure V1FO.C2FH into the water tank system. Table 5 contains an example set of sensor readings for the system at a given point in time after the failure has been induced. These can be compared to those that are expected when the system is DORMANT with the same level of water in the tank. In this case the volume flow rate and spill tray sensors exhibit readings as in scenario 6, with a decreasing rate of change. The expected readings for the system are no flow at all three valves and no water in the over spill tray (scenario 16).

Scenario	V1	V2	V3	TRAY	VOL HEIGHT	VOL RATE	S1/S2 HEIGHT	S1/S2 RATE
EXPECTED	NF	NF	NF	NW	h = Normal	$\dot{h} = 0$	h = Normal	$\dot{h} = 0$
ACTUAL	**F**	NF	**F**	NW	h = Normal	$\dot{h} < \mathbf{0}$	h = Normal	$\dot{h} < \mathbf{0}$

Table 5: DORMANT operating mode with expected and actual sensor readings for a low level of water in the tank and increasing rate of change

The height of water and rate of change calculated by the volume flow rate and spill tray sensors (located in Table 5 in the VOL HEIGHT and VOL RATE columns) are 'normal' and decreasing respectively. The readings for height and rate of change in this case are the same for the level sensors (as shown in Table 5 under the headings S1/S2 HEIGHT and S1/S2 RATE), implying that all sensors in the system are reliable. Therefore, non-coherent fault trees for the unexpected volume flow rate and spill tray sensor readings (in bold, Table 5) are combined as inputs to an AND gate together with the trees for the level sensor readings to form the top event structure for the scenario (shown in Figure 2).

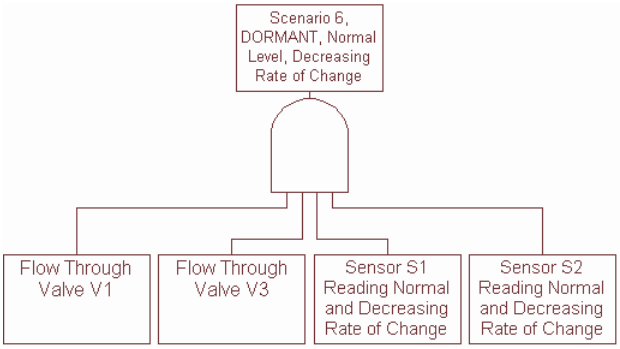

Figure 2: Top event structure for the Actual Sensor Reading in Table 5

Qualitative analysis of the fault tree produces the prime implicants; combinations of component states (working and failed) that produce the sensors readings are obtained. To eliminate the potential causes that would not produce the sensor readings that do not differ from the expected value each prime implicant is checked against the volume flow rate and spill tray sensor readings. Any prime implicant that would cause flow at V2 or water in the spill tray is not consistent with the full set of sensor readings and can be removed from the set of potential system fault conditions. In this case checking the potential causes of failure against the volume flow rate and spill tray sensors that have not deviated does not reduce the potential causes of system failure any further. Working states are removed from the potential causes to give the coherent approximation. The potential causes of failure before and after removing the working states using the coherent approximation are listed in Table 6.

Number	Potential Causes of Failure	Coherent Approximation
1)	V3FO.-V1FC.-C1FH.-P1B.-P1F.-P2B.-S1FE.-S1FL.-S1FN.-S1FH.-S1FVH.-S1FF. -S2FE.-S2FL.-S2FN.-S2FH.-S2FVH.-S2FF.-TR.-V3FC.-C2FL.-P5B.-P5F.-P6B	V3FO
2)	C2FH.-V1FC.-C1FH.-P1B.-P1F.-P2B.-S1FE.-S1FL.-S1FN.-S1FH.-S1FVH.-S1FF. -S2FE.-S2FL.-S2FN.-S2FH.-S2FVH.-S2FF.-TR.-V3FC.-C2FL.-P5B.-P5F.-P6B	C2FH

Table 6: Potential causes of Failure Obtained from the Actual Sensor Readings in Table 5

The potential causes of failure obtained in this case do not include the two simultaneous failures V1FO.C2FH that were induced into the system. Both these failures can be the cause of flow through valve V1 and flow through valve V3.

5. Discussion

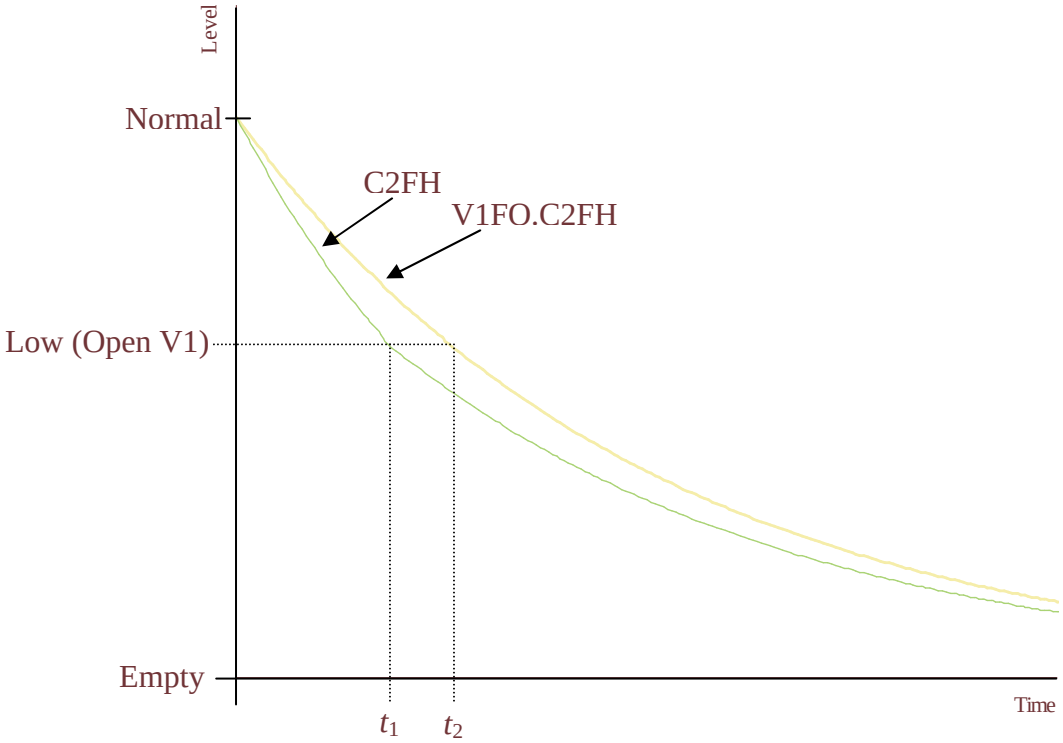

Figure 3: Plot of level of water in the tank against time for the failures C2FH and V1FO.C2FH

Figure 3 compares how the level of water in the tank would drop if the failure C2FH were induced, against inducing the two simultaneous failures V1FO.C2FH into the system whilst in the DORMANT operating mode. The level for the C2FH failure drops at a faster rate than V1FO.C2FH. When the level reaches 'low' (at time t_1 in Figure 3), valve V1 is opened to try and replenish the tank and therefore the rate at which the level is falling slows down.

The level of water in the tank does not drop as fast for V1FO.C2FH because although overall the water level is dropping for this induced failure, there is always a flow into the system. Figure 3 indicates that the level does not reach the 'low' level in this case until time t_2. These results show that time is a factor that will need to be considered in the analysis.

6. Conclusions

- In its present form the method is good at diagnosing faults in systems. However, in certain cases more research is required to obtain more accurate solutions.

- Checking the potential causes of failure obtained against the working component states from the volume flow rate and spill tray sensors that are reading true to the operating mode can assist in reducing the number of potential causes of failure. This ensures that the potential causes of failure do not conflict with the sensors reading true to the operating mode.

- The volume flow rate and spill tray sensors VF1, VF2 VF3 and SP1, and level sensors S1 and S2 provide three ways of obtaining the level and rate of change of height of water in the tank. Therefore unreliable sensors can be detected and removed from the analysis.

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