M^2CIRQ: Qualitative fluid flow modelling for aerospace FMEA applications

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Abstract

This paper presents fluid flow system simulation using the MCIRQ qualitative simulator. MCIRQ was designed as an electrical simulator, however this work exploits the close analogy between fluid flow and electrical current at the level of qualitative behaviour. The core qualitative flow algorithm is applicable to both domains but there are differences in the systems structures and assumptions that require additional modelling. The concepts of multiple source networks, and explicit propagation of multiple substances through a network, are necessary to model important characteristics of fluid flow networks. Both of these characteristics are developed on top of the MCIRQ simulator with the aim to produce an automated FMEA for aircraft fuel systems similar to previously developed automated electrical FMEA.

Introduction

This paper describes a circuit-based approach to modelling both hydraulic and fluid flow systems. The approach is based on the MCIRQ multi-level qualitative flow simulator used for simulation of electrical circuits (Lee 1999; Price, Snooke, & Lewis 2003). This work proposes two main enhancements to the simulator ontology:

- multiple pump configurations are common in fluid systems and require multiple connected power sources within a single flow network;
- an explicit representation of the substance being propagated is necessary both to reason about the effect of faults, such as leaks that allow ingress of air or escape of fluid, as well as to represent the states of components such as tanks.

These features allow simulation of many significant behaviours and potential failures of an aircraft fuel system that is the application area of this work. Important characteristics include: emptying and filling of tanks, flow of fuel and air within a system, and gravity based flow. Important faults include blocked and stuck valves, blockages in pipes and vents, pump failure and inefficiency, and leaking components.

New capability is added on top MCIRQ algorithm by allowing multiple execution of the analysis together with additional representation of substances at the connection points of the network. This additional layer is referred to as M^2CIRQ in this paper.

The focus of the work is on modelling the fuel transfer systems of multi engine aircraft. This paper presents the modelling concepts developed and a simple demonstration example, avoiding unnecessary complexity and commercial issues associated with presenting the real system.

Qualitative fluid flow

The approach taken in this work separates global system characteristics and the local causal effects of components. The global flow behaviors are predicted by MCIRQ, leaving the modeler with only component behavior to define. This creates a more natural modeling environment than can be the case with general qualitative constraint systems such as QSIM (Kuipers 1994) or (Kitamura, Ikeda, & Mizoguchi 1996), although the latter author deals with thermal effects in addition to flow characteristics. The MCIRQ circuit analyzer described in (Lee & Ormsby 1994; Lee 2000) is a global flow based simulator and we exploit the analogy between electrical current and fluid flow as discussed in (Chittaro & Rannon 1999) however there are several significant differences:

- Electrical systems normally only have a single power source, but fluid systems often have several pumps used in different operating modes or configurations. If gravity feed is present or siphonic behaviour is required then gravity can me modelled as a weak pump for example.
- Several significant substances may be required in a fluid system in contrast to electrical systems.
- The movement of the fluid is far more significant in fluid systems than flow of charge in electrical systems.
- The storage of substance and the energy sources (pumps) are not usually the same component as is the case for a battery or PSU.
- The gross movement of charge –for example battery discharge– is often ignored in electrical analyses, however the capacity and storage of fluids and gasses in fluid systems is central to the system operation.

Overview of MCIRQ

MCIRQ provides qualitative order of magnitude analysis of resistive networks. A network is comprised of a set of *arcs* that represent resistances. Each arc is associated with exactly two *nodes*. Two arcs are connected if they share a node. MCIRQ requires a resistive value to be assigned to each arc from an order-of-magnitude sequence. The minimal set of resistance values is $\{\mathrm{zero} < \mathrm{load} < \mathrm{infinite}\}$, although this work uses five levels for electrical and fluid circuits. Each network has exactly one positive (+) node and exactly one negative (-) node.

Figure 1 shows a network using the resistive values $\{\mathrm{zero} < \mathrm{low} < \mathrm{medium} < \mathrm{high} < \mathrm{infinite}\}$. The resulting analysis is shown as the flow values from the ordered set $\{\mathrm{F}_0 < \mathrm{F}_{\mathrm{low}} < \mathrm{F}_{\mathrm{medium}} < \mathrm{F}_{\mathrm{high}} < \mathrm{F}_{\mathrm{short}}\}$. The details of the analysis algorithm are presented in detail in[Lee00a].

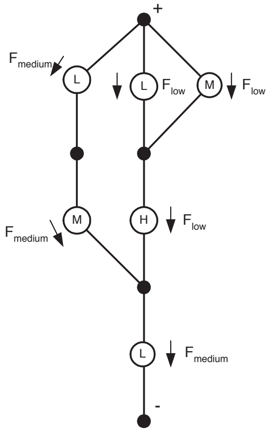

Figure 1: example MCIRQ network

Modelling circuit components

MCIRQ represents the structure of electrical components as resistances. A wire is a single resistance with value zero, a switch is represented as zero in its closed state and infinite in its open state. A lamp or other power-consuming element is represented by a non zero resistance dependent on its power consumption. In this work fluid circuit components are similarly represented; pipes provide a zero (or low) resistance, valves provide zero or infinite resistance for the open and closed states. A battery or power supply provides the positive and negative power terminals for an electrical circuit and pumps provide power terminals for fluid circuits. These terminals are mapped to the positive and negative network nodes.

The structure is changed by the state of valves and switches. Higher level component behaviour is represented by a model, such as a finite state machine, that is able to change state based on the results of the network analysis (Price *et al.* 1997; Snooke 1999). This in turn may trigger a structure change and new network simulation; the cycle is repeated until a steady state, cyclic behaviour, or ambiguity is detected.

Example system

Figure 2 shows a system using both electrical and fluid based components, and is to be used as a running example in the remainder of this paper. A CAD tool generates a netlist itemising each component and providing a connection list. The circuit represents two fuel storage tanks connected by a sequence of pipes, an electrically driven pump, and a mechanically operated bidirectional pump.

A component called atmosphere is also present in Figure 2 to model the flow of air between the tanks and completes the circuit. The atmosphere component model also allows leak faults to be simulated. Most faults are local to a component such as wire open circuit, or valve stuck open; however leak faults are analogous to electrical short to battery and short to ground faults, and require a change to global circuit structure. For specific modelling domains and tasks, abstract components such as atmosphere can be included in the translation from schematic to netlist to make the schematic drawing stage more intuitive. For clarity atmosphere is explicitly represented in this paper.

Multiple sources

Modelling multiple sources is approached using the principle of superposition. Superposition states that linear systems with multiple sources can be analysed by composing (i.e. summing) the results of separate analysis for each source. This is achieved in M^2CIRQ by executing MCIRQ for each pair of power nodes with all other power nodes removed and shorted with a zero resistance. Each arc in the network will have n current flow magnitude and direction values for a network with n sources. This of course may lead to qualitative ambiguity. For FMEA tasks this is not usually a problem; in fact it often provides useful information about the potential system behaviours. Indeed even a single source can generate ambiguous flow directions, for example in the case of a bridge circuit, although empirical evidence suggests that -even for electrical power systems- this occurs only when failures are being modelled; and then only rarely. Often such ambiguity has no long-term effect on the system behaviour and therefore does not cause simulation problems. In general, information about any ambiguity is passed to the analysis tool that initiated the simulation, where it is interpreted to provide information about the system level behaviour characteristics. The qualitative flow for the network is resolved for each arc as follows:

1. consider *only* the flows with the highest magnitude for each arc
2. if any flows are ambiguous the arc result is ambiguous
3. if all of the flows are in the same direction this is the result, otherwise there is a qualitative flow ambiguity for this arc

The previous paragraph applies to a *connected* network with multiple sources. A netlist such as the example system in figure 2 is easily partitioned automatically into two distinct networks: an electrical network containing the battery; and a fluid network containing two pumps. The simulator builds the system structure by creating and connecting all of

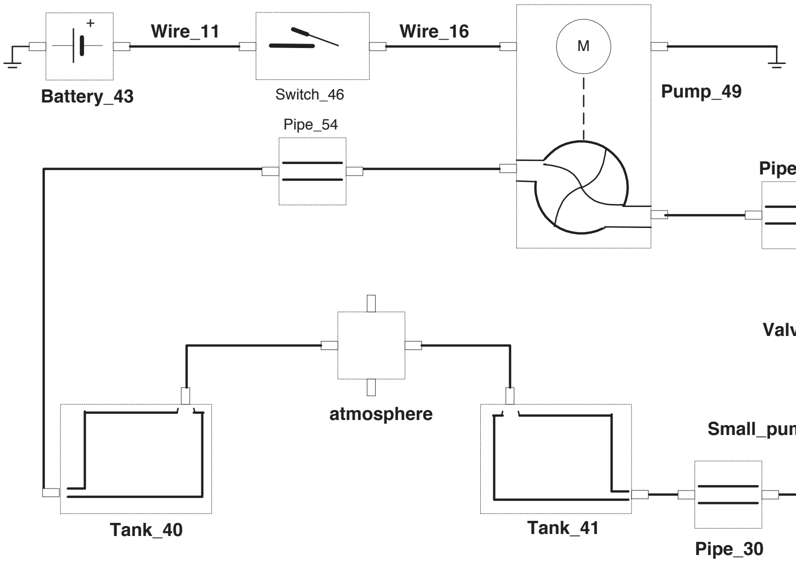

Figure 2: simple mixed circuit schematic

the component structure fragments. The network is then partitioned into disjoint subsets of nodes and arcs that represent separate networks. A component may of course belong to more than one network, for example the pump in the example. Notice that terminals may be typed to allow the drawing tool to do some checking to help prevent mistakes such as accidentally connecting elements from different domains. The simulator does not need to consider types, it simply uses the connection topology to partition networks. Indeed, several networks may be found for each domain, particularly for fluid systems that have several circuits flowing through common components. Of course if a component failure mode is being used that represents a connection between otherwise separate circuits then they will be connected, although the multiple source analysis will only produce a flow in the correct part of the circuit when the fault is not active. M^{2}CIRQ generates two networks for the example in figure 2 and produces the expanded component structure in figure 7.

Substance Propagation

It is desired to model the emptying and filling of tanks and the effects of leaks. The models therefore require that component state models can detect the substance flow present at inputs and outputs. Substance propagation between components naturally occurs at nodes, as the interface between components, and is dependent on flow direction. In the simple case of two connected components A and B, a substance is propagated into a node by the output component A, and received by component B input. In a complex circuit there may be several connections to a node and flow direction may change during simulation. For these reasons a list of substances is maintained at each node, and contains the output substances of each arc connected to it at any step of the simulation. Figure 3 depicts a node connected to three arcs.

Each node has the postfix symbol .SUBSTANCE available for assignment and evaluation by the component model (for example as part of a FSM event action). This is a consistent extension to the .RESISTANCE and .FLOW symbols available for the assignment of resistance and evaluation of flow already present for arcs.

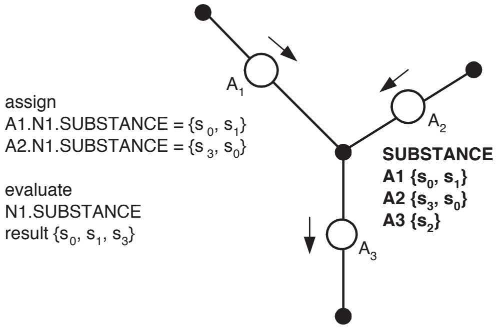

Figure 3: Node substance representation

Assignment to a node requires the arc associated with the substance and simply results in a list of substances being set for the required arc. Accessing the substance for a node within the model is straight forward as in the following example taken from the component description of a pipe.

```
IF resistance.FLOW == 'FORWARD'
  {resistance.T2.SUBSTANCE = T1.SUBSTANCE}
IF [resistance.FLOW == 'REVERSE'
  {resistance.T1.SUBSTANCE = T2.SUBSTANCE}
```

The simulator has work to do to evaluate the substance present at a node. It must consider the current flow directions for each of the connected arcs and produce a union of the substance lists associated with only the arcs that have flow directions into the node.

Modelling fluid components

The previous two sections have provided the capability to qualitatively model fluid flow systems. This section will detail the models for several components.

Using MCIRQ levels. The order of magnitude levels have been used with 5 levels to model normal flow, abnormal high flow (e.g. serious pipe fracture) and abnormal low flow (e.g. small leak). Zero flow occurs when blockage faults or valves are closed. Infinite flow or short circuit does not generally occur because even pipes are modelled as having some resistance.

Tanks

Tanks may be modelled with a number of states to represent the qualitative changes in the amount of substance contained. In the example only two states -empty and full- are provided. Qualitative order of magnitude time periods can be used in FSM based component behaviours and clearly these must be global to the entire system, since electrical and fluid system events may occur over the same time periods. The example uses an ordered set of time periods $\{\mathrm{instantaneous} < \mathrm{uS} < \mathrm{mS} < \mathrm{S} < \mathrm{Hour} < \mathrm{steadystate}\}$, although any sequence can be defined as long as they conform to the assumption that any number of events occur in one time period will take less time than an event in the next longest period. An infinite number of events in a single timeslot will generally signalling a modelling error. In practice this is unlikely to occur because most accidental infinite modelling loops will be terminated at the end of the first iteration by the simulator, which stops if a previously encountered state is reached. Mistakes with counter variables within models are the most likely culprit since the counter will prevent the system from reaching an identical state. Electrical and fluid systems do not generally require counter variables, which should be used with care when modelling software in electronic control units.

The time period used for the duration of the empty and fill events for the tank will determine its qualitative capacity, for example:

FLOW	Small tank	Medium tank	Big tank
low	Hour	Week	Month
medium	S	Hour	Week
high	mS	S	Hour

In this model a medium tank experiencing a medium flow would empty or fill in the hour order timeslot. Thus a low flow such as a small leak will cause the tank to empty in the order of week. This allows the prediction -if this tank were an aircraft fuel tank- that it would likely not imminently run out of fuel. A medium leak would cause a behavioural ambiguity indicating that the aircraft may run out of fuel and numerical information is needed. A major fracture indicates that the tank must be isolated if possible and no fuel transfers should be made into this tank (to balance the aircraft for example).

Tanks are usually designed for a specific range of substances and therefore it is reasonable to include these in the models. If an unrecognised substance is found flowing into a tank it can be made to enter an unknown behaviour state, reported to the higher-level analysis (it might be chemically attacked for example). For a fuel tank, fuel and air are the two substances the tank is expected to contain. The behaviour of the outlet, vent and contents are defined by the states of the tank. In the empty state air will flow out of the outlet, in the full state fuel will flow from the vent if flow in into the tank. Figure 4 shows this behaviour for the tank model used in the example and includes events related to flow magnitude, substance and direction.

Vented tanks have a fairly intuitive connection to the atmosphere that allows the flow of air between any number of tanks. A question arises if a tank is not vented such as for a pressure vessel. Closer inspection reveals that there remains a connection to the atmosphere, since a pressure differential will exist when as the tank is pressurised or evacuated, similar to the charging of an electrical capacitor. The connection to the atmosphere is maintained providing a logical circuit flow, although no substance is allowed to pass to the atmosphere. Once the vessel is pressurised it will become an infinite resistance to flow and may also then be modelled as a pressure source.

If the tank is in a situation where the orientation could change (for example in a aerobatic aircraft) then additional states may be required to model the movement of the fluid for example fuel entering the vent in certain orientations. If inversion is a feature of a system then all components with orientation dependent behaviour changes must be built to respond to an orientation change event, which is considered to be a system level event. All the events in the example model are component level.

Pipes

A generic pipe can be modelled with either zero resistance or a resistance value that represents the energy required to transfer the substance through the pipe. This energy may be required because the pipe bore is small or it may represent the energy required to overcome gravity if the pipe has a vertical element.

In the case where drain of substance by gravity is a feature of the system then gravity could be represented as a (small) pump(s) whose effect is overcome by normal system pumps, but causes flow when the pumps are inactive. Including several gravity pumps as part of a pipe model will possibly lead to flow ambiguity if they have opposing directions, for example in a siphon. In these cases system constraints that state relative pump sizes, may allow the ambiguity to be resolved, at least for simple topologies if not for the general case. Failing this numerical methods are required for the ambiguous region of system behaviour.

The pipe model will transfer substance from one terminal to the other dependent upon flow direction. If a pipe is considered to have small capacity this can be modled as an instantaneous event. For pipes with significant capacity or length a delay can be associated with this change of state and the pipe becomes similar to a small tank being filled with various substances. The pipe model used in the example is shown in figure 5. Event names are bold type and actions are contained in curly braces.

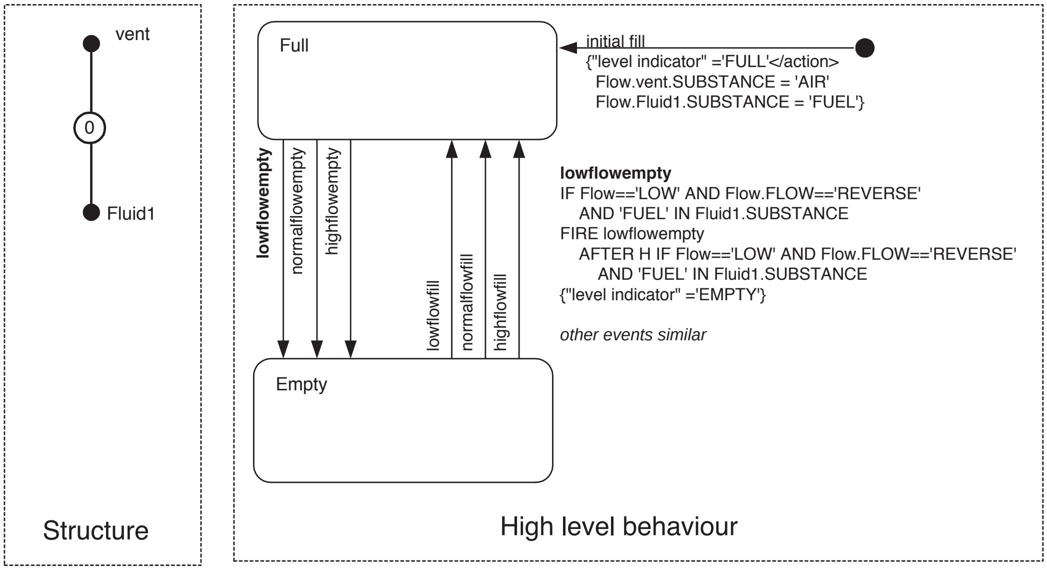

Figure 4: Tank model

Pumps

The pump acts as a transducer converting electrical or mechanical energy to a fluid pressure/flow. The pump is therefore a source for the fluid circuit and a load on the electrical one. The electrical pump becomes active when current flows through the motor causing a fluid source to be activated in the pump circuit.

For self priming pumps flow exists regardless of the substance at the terminals, non priming pumps only allow flow if the required substances are present at the input by presenting an infinite resistance in this condition.

Pumps may act as a blockage or a low resistance when not operating dependent on their design. A pair of source nodes are normally an open circuit requiring an additional resistance if the pump is to be free flowing when inactive. Pump_49 in figure 2 is an example of a free flowing inactive pump. Bidirectional pumps require the polarity of the source to be changed and can be modled as the SmallPump if figure 2, by four resistances operating in pairs based on the required pump direction. This approach saves forcing M^{2}CIRQ to analyse one circuit for each source polarity when clearly only one can ever be connected outside the pump component for any given simulation

The atmosphere

Leaks are the significant global fault for many fluid circuits. To simulate these situations the fault model of a component must make a connection to another component. The electrical analogy for a leak is a connection to the negative terminal of the source, but this is problematic because a leak may not only cause substance to escape, but may cause substance (e.g. air) to be drawn in on the negative pressure side of a pumped circuit. From the modelling perspective a leak should behave correctly for both situations. In addition the substance of the leak must be considered unlike the electrical case. An explicit model the atmosphere as a component provides a solution. A connection can then be made to the atmosphere for any leak faults. If the atmosphere is not otherwise used in the circuit, for example in a sealed hydraulic system, it is connected to the negative pump terminal(s) to provide the correct flow circuit.

The atmosphere model assumes an infinite capacity for inflow of substances and will always provide air if substance flows out of the atmosphere. The atmosphere component is essentially a connection point, although it is useful to provide a dedicated terminal to use to connect other components that have leak faults because air flowing out of these fault connections can be reported as air ingress into the system. The atmosphere can also be made to recognise and report substances other than air flowing into it since this may occur when vents overflow for example.

Example system

Simulation

Figure 6 demonstrates the simulator being driven manually. In this example a system level statechart[1] is being used to provide external inputs to the system. This deliberately causes the simulation to stop after S timeslot events because the system statechart has ambiguities (i.e there are a choice of switches that can be changed within a S time period). The user is asked to select from the ambiguous events. An example highlighted in figure 6 and displayed in the lower frame.

In this example the user selected to close the electrical switch, and then to open the valve. Fuel is transferred from one tank to the other in the Hour time period because the

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[1] the system statechart is automatically generated from all component interface variables that are read (only) by each component model

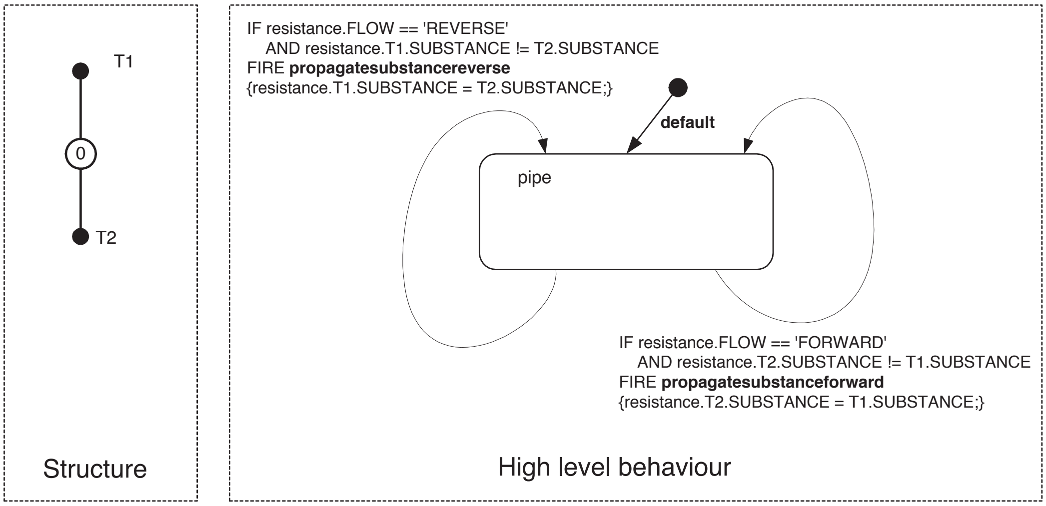
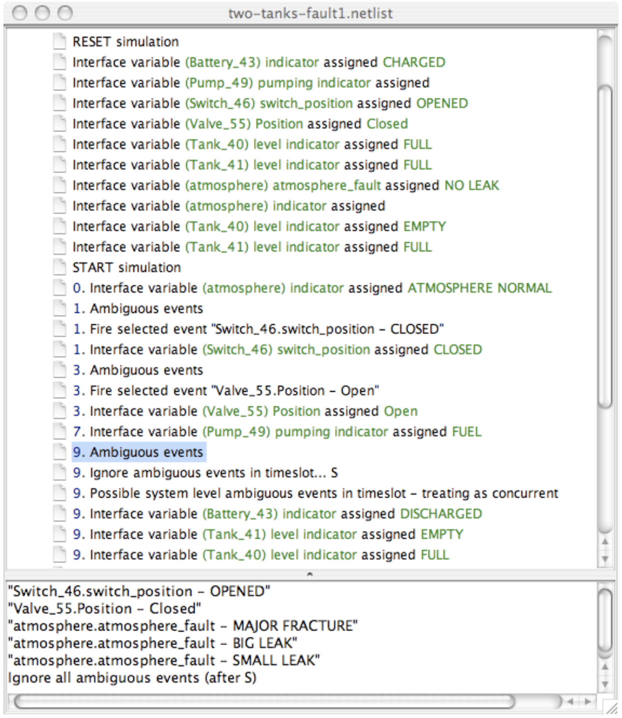


Figure 5: Pipe model

user did nothing in the highlighted S time period. The flow during this period is shown in figure 7 where the nodes are annotated with the fuel and air flow through the system.



```
RESET simulation
Interface variable (Battery_43) indicator assigned CHARGED
Interface variable (Pump_49) pumping indicator assigned
Interface variable (Switch_46) switch_position assigned OPENED
Interface variable (Valve_55) Position assigned Closed
Interface variable (Tank_40) level indicator assigned FULL
Interface variable (Tank_41) level indicator assigned FULL
Interface variable (atmosphere) atmosphere_fault assigned NO LEAK
Interface variable (atmosphere) indicator assigned
Interface variable (Tank_40) level indicator assigned EMPTY
Interface variable (Tank_41) level indicator assigned FULL
START simulation
0. Interface variable (atmosphere) indicator assigned ATMOSPHERE NORMAL
1. Ambiguous events
1. Fire selected event "Switch_46.switch_position - CLOSED"
1. Interface variable (Switch_46) switch_position assigned CLOSED
3. Ambiguous events
3. Fire selected event "Valve_55.Position - Open"
3. Interface variable (Valve_55) Position assigned Open
7. Interface variable (Pump_49) pumping indicator assigned FUEL
9. Ambiguous events
9. Ignore ambiguous events in timeslot... S
9. Possible system level ambiguous events in timeslot - treating as concurrent
9. Interface variable (Battery_43) indicator assigned DISCHARGED
9. Interface variable (Tank_41) level indicator assigned EMPTY
9. Interface variable (Tank_40) level indicator assigned FULL
```

```
"Switch_46.switch_position - OPENED"
"Valve_55.Position - Closed"
"atmosphere.atmosphere_fault - MAJOR FRACTURE"
"atmosphere.atmosphere_fault - BIG LEAK"
"atmosphere.atmosphere_fault - SMALL LEAK"
Ignore all ambiguous events (after S)
```

Figure 6: Simulation

Failure simulation examples (broken pipes)

Figure 8 allows the input of pipe_54 to be connected to the atmosphere to simulate a leak fault. Normally, a failure mode analysis tool inserts such faults programmatically; it is done manually here to allow the effect to be seen visually. The atmosphere can include three qualitative levels of fault and the leak in this case is caused by a Low resistance connection to the atmosphere. In addition the second pump has been activated in the same direction as the main pump, accordingly, the simulator shows twin flow arrows on the connections. The resulting flow is shown inside arc (hollow circle) symbols.

Figure 9 shows the situation where a small leak is created at the valve end of pipe_22. Air can be seen being drawn into the system by the pump, and propagated through the system. In colour reproduction the flow magnitude is indicated by the simulator, and in this case can be seen to be medium (green) for fuel, and fuel/air mix through the main circuit, with a low (cyan) flow of air between atmosphere and the small leak.

Conclusion and future work

The additions to the modelling do not affect the electrical circuit simulation or models and these are simulated as in earlier work, using the same models. These models have no substance included and only one voltage source is present and are therefore simply a subset of the new modelling and simulation capability.

Fluid and electrical circuit characteristics

The characteristics of electrical and fluid circuits are different. Fluid circuits often have multiple sources, however the topology of fluid circuits is often simpler than electrical circuits, in particular normal operating configurations of valves often reduce a specific operating model to a series circuit. This (by empirical observation) reduces the ambiguity of flow that might otherwise be expected, to a small number of failure cases. Further study of more complex systems will be carried out to verify these observations.

For electrical circuits five MCIRQ levels have been used to distinguish between signal and sensor inputs($<$1mA), and

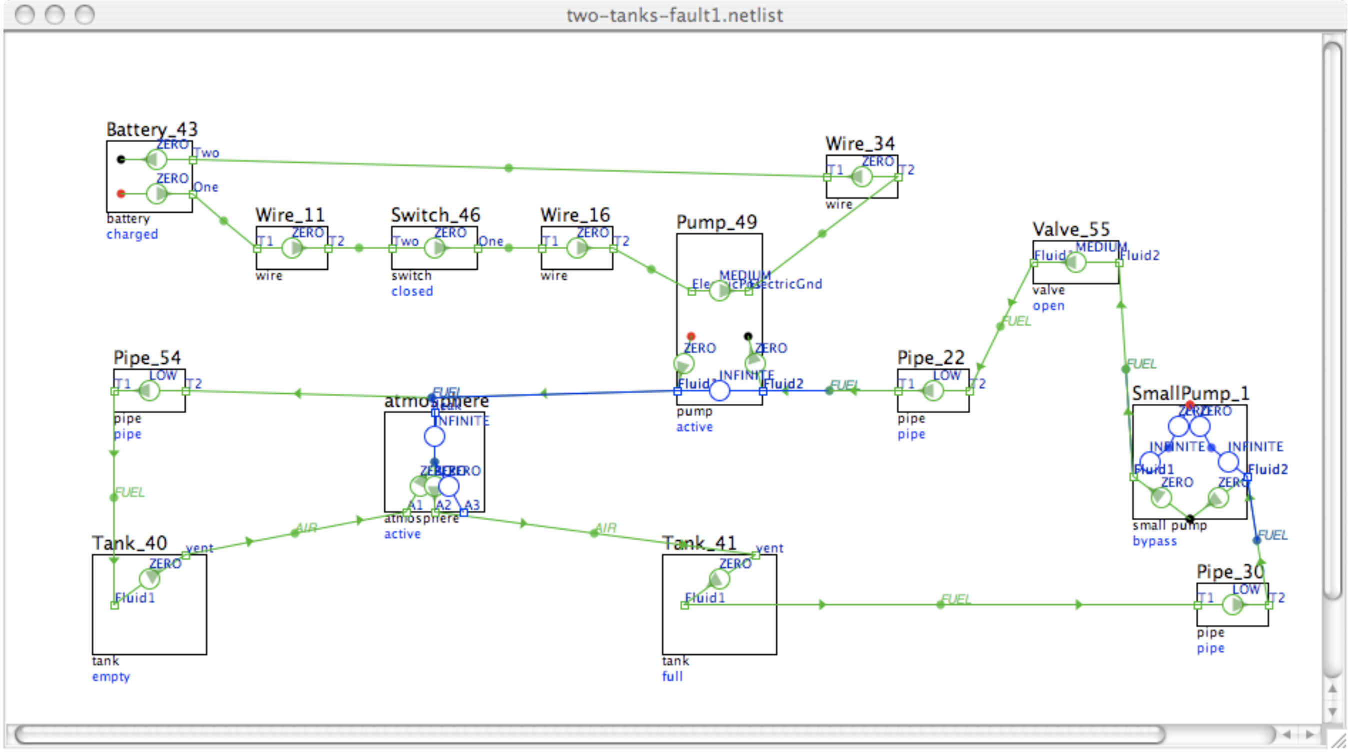


Figure 7: Simulation

low power devices such as relay coil inputs(10mA flows) and high power devices (Amps). This has allowed the analysis to ensure that a relay signal level flow would not light a car headlamp for example. In the fluid analysis it appears there is rarely a deliberate qualitative magnitude difference in flows within a system and a more useful distinction is within the failures that can exist. This is certainly the situation for aircraft fuel systems. Clearly a minor seepage leak and a major fracture have very different impacts on the behaviour of an aircraft fuel system, for example. These two distinctions again lead to a five level qualitative flow analysis. Zero, medium, and infinite resistance model normal operation. Low and high resistance are used in addition to represent faults.

Circuits with different voltage sources or batteries can easily be created and can be useful for example to model power transformers, or separate analogue and digital circuits, but faults connecting the circuits have not yet been investigated.

Substance representation within models

Some component models may be defined to operate with any substance, for example a generic pipe. Many components require behaviours that depend on the substance that is flowing, so that a tank does not fill if air is flowing into it. To some extent this limits the use of a component model to the types of system it was designed for, however this is realistic in many cases since most components will only operate as intended with the correct substance. It is useful if library models include 'behaviour out of specification' states to signal the limit of their behaviour has been reached if unknown substances are detected. It is perfectly possible to create a set of components and substances that are very generic such as liquid and gas for abstract modelling applications.

The representation of substances allows for the presence of more than one substance to flow through a connection. No modelling of mixing or separation processes are modelled with the exception that tanks always have air at the vent unless overflowing and this is adequate for the fuel transfer and hydraulic applications.

Non-linear components

The analysis of multiple sources relies on the linear resistance representation used by CIRQ. Non-return valves are the main fluid flow component that does not approximate to a linear flow component in a qualitative representation, and, unsurprisingly, have similar issues as encountered for electrical diodes. For many circuits these can be modelled as a state based component (zero/infinite resistance) with an extremely high impedance leakage resistor in parallel to detect voltage direction (voltage is not explicitly generated by CIRQ because there may be many levels required and they are not qualitatively significant across most components). This provides a requirement for a special qualitative resistance level directly below infinite, that results in a current flow that does not affect the system.

Conclusion

The network analyser enhancements have been implemented and allow variety of fuel system faults and features to be modelled. Faults include leaks and blockages, stuck and leaking valves, broken and faulty pumps, leaking tanks. System characteristics modelled include fuel flow and routing through multiple tank, multiple multi port valves. The emptying and filling of tanks and the qualitative time involved. The atmosphere is modelled allowing the egress and ingress of fuel and air from the system to be derived. An automated FMEA has not yet been generated using the simulator, but it should provide a similar level of system level results as the electrical only version. A variety of realistic fuel system models are being constructed.

Acknowledgements

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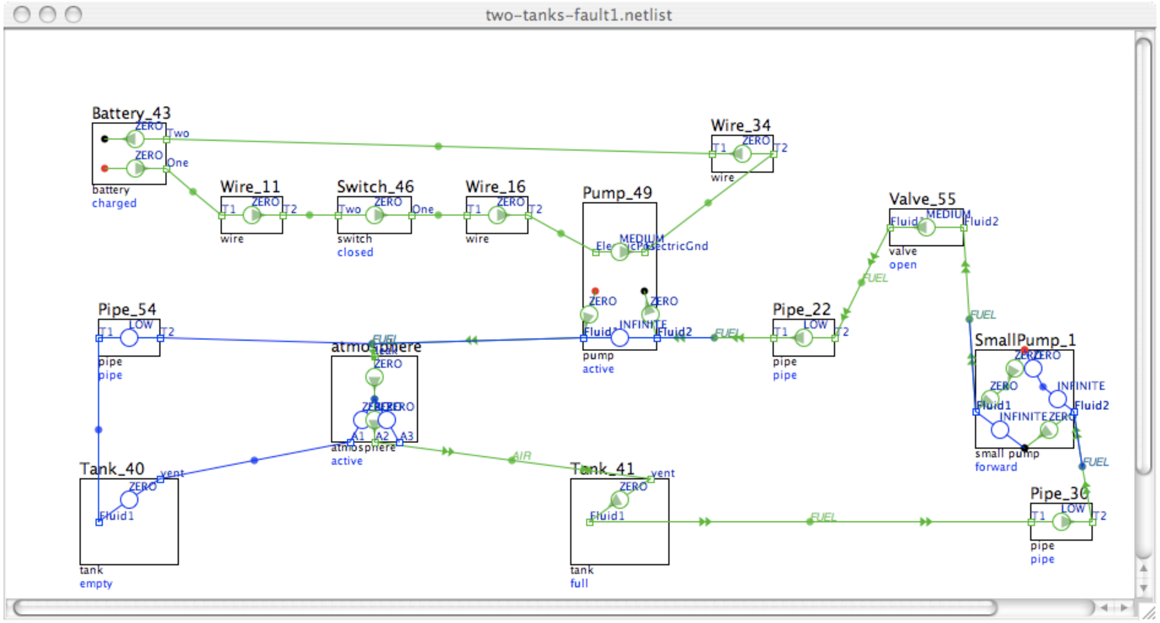

Figure 8: Major leak

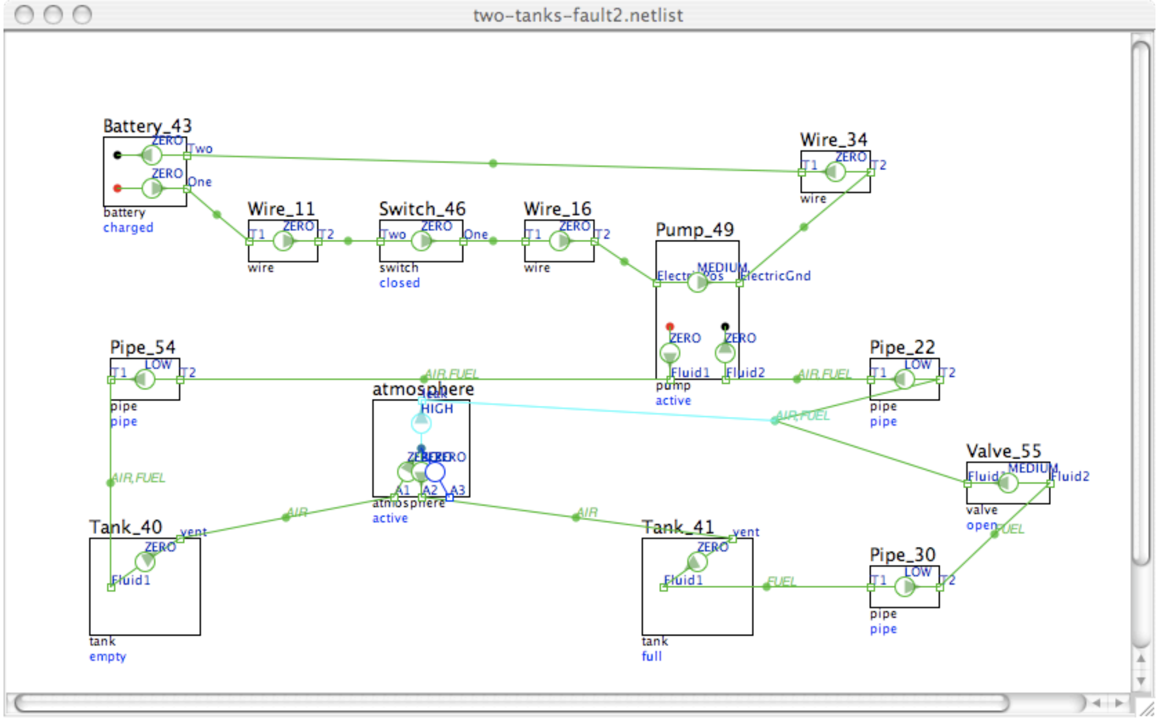

Figure 9: Small leak