Implementing a Real Time Reasoning System for Robust Diagnosis

Tim Hill
William Morris
Charlie Robertson
McDonnell Douglas Space Systems Company
Space Station Division
16055 Space Center Boulevard
Houston, TX 77062
hill, morris, ccr
@kbs.mdc.com

Abstract

The objective of the Thermal Control System Automation Project (TCSAP) is to develop an advanced Fault Detection, Isolation, and Recovery (FDIR) capability for use on the Space Station Freedom (SSF) External Active Thermal Control System (EATCS). Real-time monitoring, control, and diagnosis of the EATCS will be performed with a Knowledge-Based System (KBS). This paper describes implementation issues for the current version of the KBS.

The TCSAP KBS is a combination of three distinct elements that interact with each other. The first is a quantitative model of the EATCS, providing step-wise steady state values for any EATCS configuration. The model is used in sensor validation and component diagnosis by comparing observed sensor readings with their computed values. Inconsistencies between observed and expected values imply either instrumentation failure or actual off-nominal behavior of the EATCS. The second element is a rule-based system containing safety critical and non-critical FDIR rules focused directly on the EATCS. The rules use both quantitative and qualitative values for reasoning and diagnosis. Quantitative sensor values are obtained from an external source and qualitative representations are derived from the history of the quantitative data. The third KBS element is the Human Interface (HI). The HI implements graphically oriented monitoring and control capabilities for the EATCS. The interface attempts to "intelligently" support the operator by supplying information of the type and quantity most likely needed in a given context. The HI also allows the user to specify configuration changes such as the closing or opening of a valve. These changes can be transmitted to the EATCS hardware as well as affecting the internal KBS quantitative model.

The KBS utilizes conventional software and a real-time expert system tool called G2. The use of G2 eases development of reasoning techniques required for automating the EATCS monitoring, control, and FDIR tasks. The resulting KBS utilizes a combination of model-based sensor validation, rule-based fault descriptions, and model-based diagnosis of unanticipated faults.

EATCS Overview

The External Active Thermal Control System (EATCS)[1] of Space Station Freedom (SSF) provides cooling and control necessary to maintain elements, systems, and components within their required temperature ranges. The EATCS design has evolved from the single-phase fluid system used in Apollo and Space Shuttle to a two-phase system (ammonia liquid and vapor mixture) on SSF. Both active and passive components of the EATCS can potentially fail or become blocked. As a result, a variety of failure modes exist. When this is combined with the continuous range of normal operating conditions and issues related to two-phase flow, EATCS diagnostics can become very complex.

The Space Station EATCS is a central facility, transporting waste heat away from crew quarters, experiment packages, computers, DC-to-DC power conversion units, etc., and radiating it into space. It utilizes ammonia as the working fluid and interfaces via heat acquisition devices (HADs) with the habitation and laboratory modules, and truss mounted equipment where the heat dissipation rates are too high to be controlled passively. HADs are heat exchangers and cold plates that remove heat directly from fluid systems and electronic equipment. Liquid ammonia is supplied to the HADs by the EATCS and is vaporized by the particular heat load being serviced. The vapor is transported to the radiators which reject heat to space. Figure 1 shows a functional configuration of the major EATCS components included in a single loop or bus.

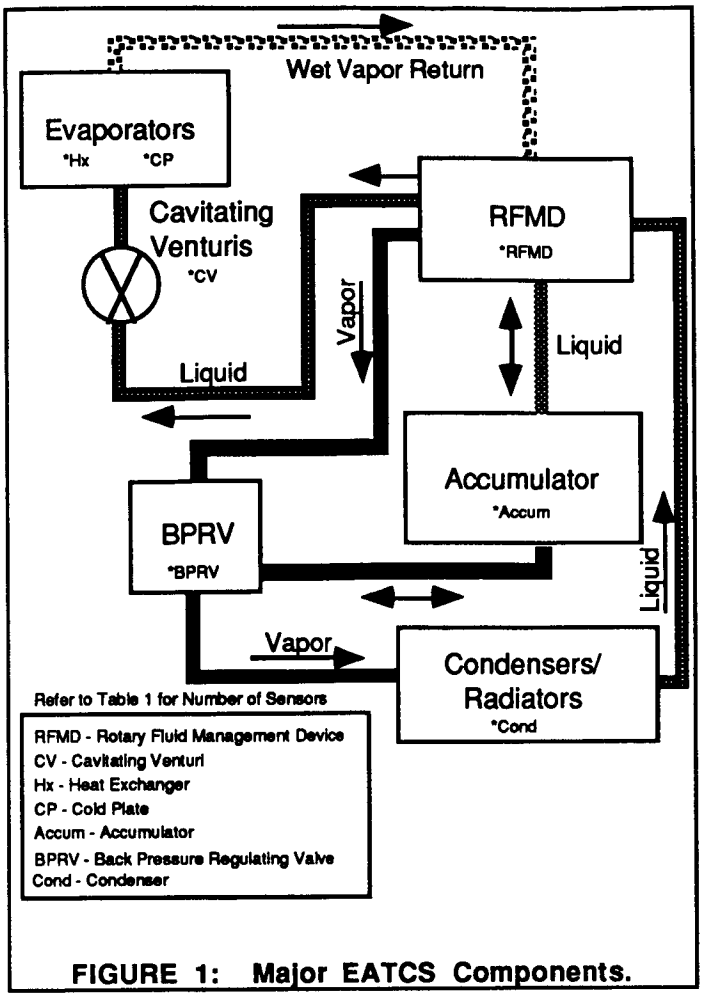

FIGURE 1: Major EATCS Components.

Table 1 shows the number of sensors for the major components shown in Figure 1.

TABLE 1: Number of Sensors and Location

Loc.	Temp	Press	DP	Flow	Other
RFMD	5	2	3	2	2
CV (5)	5	0	5	5	0
Hx (3)	6	6	0	0	0
CP (2)	2	2	2	0	0
Accum (2)	2	0	1	0	2
BPRV	1	0	0	0	1
Cond (2)	6	5	3	2	0
TOTALS	27	15	14	9	5

KBS Overview

The Thermal Control System Automation Project (TCSAP) Knowledge-Based System (KBS) is a combination of three distinct elements that interact with each other.[2,3] The first is a quantitative model of the EATCS, providing step-wise steady state values for any EATCS configuration. The second element is a Rule-Based System (RBS) containing safety critical and non-critical FDIR rules focused directly on the EATCS. The third KBS element is the Human Interface (HI). The KBS utilizes conventional software and a real-time expert system tool called G2.

Model Development and Use

The internal simulation model used by the KBS for sensor validation is an object-oriented reconfigurable model centered around the actual major EATCS components and their connectivity (Figure 2). The model is used in three key areas by the KBS as discussed further in this paper: (1) to perform sensor validation, (2) to provide transition points for mapping sensor data to qualitative states in the RBS, and (3) to provide expected operating conditions to the HI. Each component modeled contains state variables associated with inlet and outlet conditions. These state variables are flow rate, temperature, pressure, and quality (vapor mass divided by the sum of vapor and liquid mass). Constraints are represented by generic rules and mathematical formulae that govern the relationships among these state variables and their propagation through the components of the thermal bus. These constraints are based on the laws of physics and thermodynamics (e.g. conservation of mass), as well as the actual component design parameters (e.g. device specific pump head curves).

Sensor objects can be logically connected at the inlet or outlet of any component in the model to represent actual sensor locations. At these points, sensor readings can be compared with the model-predicted value to perform sensor validation and initiate component fault diagnosis. Reconfiguration of the model occurs automatically from changes in heat loads, pump speed, set point temperature, or isolation valve positions in the monitored hardware.

Several simplifying assumptions were made during the building of the model. The foremost simplification in the current model is to support only steady state conditions. The model "propagates" from one steady state to the next without regard to time lags or transient states. Another significant assumption is the adiabatic behavior (no heat transfer) of all components except heat exchangers. Other assumptions in the current model are that the bus will absorb the total heat load, and that flow will always be in one direction.

A major goal in building this model was that it be as generic as possible, so that maintenance would be greatly simplified. Another goal was to have a model which could support model-based reasoning for sensor validation and component diagnosis. We do not attempt to encode a global set of equations or a solution strategy in this model. Instead, state variables are propagated across components and from one component to another either upstream or downstream according to the generic constraints previously discussed. This propagation occurs until all state variables converge to steady values (within some tolerance).

Input design and configuration parameters for the model include the flow-rate of every cavitating venturi, the design heat load of every evaporator, the design heat rejection capability for each condenser, the initial accumulator positions, and all valve states. The total condenser cooling capacity and the estimated average condenser subcooling are also calculated. Regularly supplied external configuration information includes: the heat load on each evaporator, the commanded setpoint temperature, and the RFMD motor speed. Using these facts and assumptions the KBS model is able to propagate between steady states.

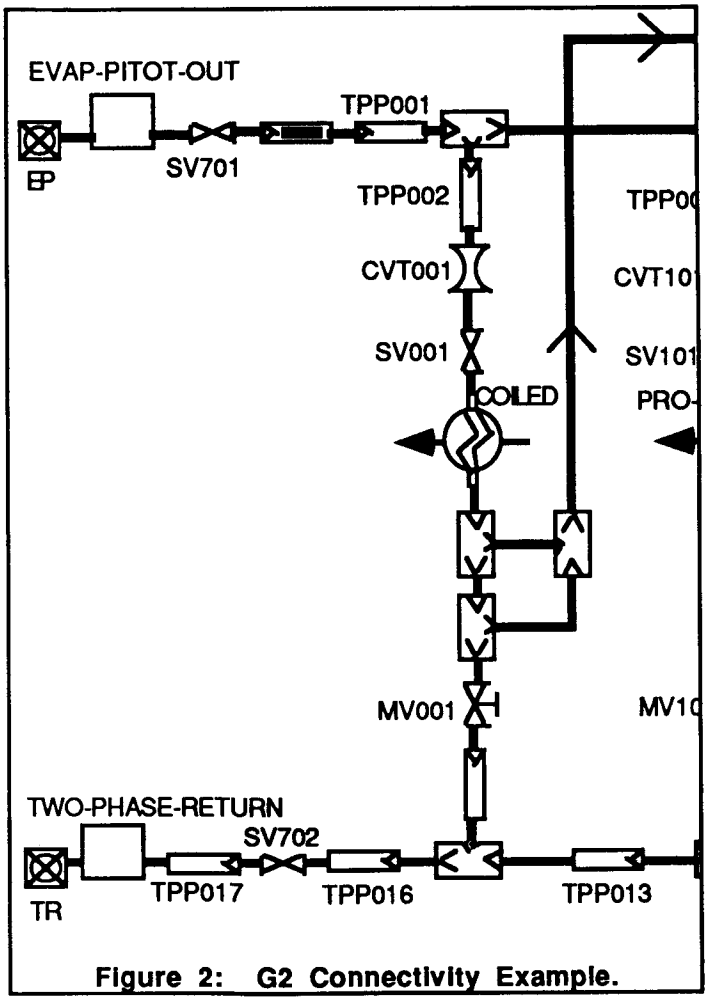

Figure 2: G2 Connectivity Example.

The KBS model is propagated with the assumption that the bus is operating nominally. In fact, both nominal and off-nominal operating conditions cover continuous ranges. For example, if one evaporator has been shut down, the re-configured bus can still be viewed as operating nominally. The bus would reach a new steady state reflecting a configuration with one less evaporator. Similarly, there is no discrete distinction between off-nominal behaviors. Conditions considered nominal in one state might represent a fault scenario in a different operational mode. An infinite number of combinations are possible. This makes the use of a model even more appropriate in attempting sensor validation and fault diagnosis.

For sensor validation, the observed sensor readings at each point are compared with the corresponding computed values in the model. If the two values (sensor reading versus computed value) are not within tolerance then the sensor is marked as suspect. If sensor validation finds a sensor reading to be suspect, then the sensor will be monitored for fifteen seconds. Fifteen seconds is ample time to allow other sensors to go out of their application limit range, indicating that a fault is occurring. After fifteen seconds, if the sensor reading has not changed or the model still invalidates it, then that sensor is automatically failed. A failed sensor on-orbit may not be replaceable for several months, so working with the instrumentation available is imperative. Each sensor definition has the capability of specifying backups. A more detailed description of the backup sensor implementation is given in the next section (Rule-Based System).

The model-based reasoning for component diagnosis portion of the KBS is still in development. Several different approaches [4,5,6,7] are being implemented in parallel efforts. The strengths and weaknesses of each technique will be described in a separate report.

Rule-Based System

The design intention of the KBS is to represent thermal expertise in the same way it is expressed by the thermal engineer. The comparison of observed values to expected values as described earlier is exactly what a human expert does implicitly. Complimenting this model-based view of the problem an expert also applies heuristics, lessons learned from experience, that can often be expressed in the form of if-then rules. The KBS uses such forward chaining rules in a Rule-Based System (RBS) to perform fault diagnosis.

The TCSAP RBS attempts to match rule conditions against patterns of system status information. The RBS has several advantages over traditional table-driven approaches to diagnosis which also match sensor readings to target values (in tables). The RBS rules represent diagnostic knowledge at a high level, allowing easier human interpretation, maintenance, and meaningful explanation capabilities. The RBS is not tied to a specific EATCS configuration. The data-driven nature of rule-based systems combined with support code for primary and alternate instrumentation allows the RBS to degrade more gracefully than a table lookup approach.

The FDIR rules reference qualitative states (e.g. low, nominal, high) and trends (e.g. decreasing, steady, increasing) to aid in development, interpretation, and maintenance of the RBS. Each sensor has qualitative mappings for current value and trend information[8]. Transition points for qualitative states are predefined but

can be dynamically modified such that a quantitative value range corresponding to a qualitative state of "low" may be different depending on the current system mode. For example (see Table 2), the qualitative state of a particular thermocouple might be nominal if the reading is above 58°F and below 66°F with a setpoint temperature of 62°F. Low, very-low, high, and very-high would map to other ranges. The trend of each sensor is translated in a similar way. The qualitative trend states include: rapidly-decreasing, decreasing, steady, increasing, and rapidly-increasing.

TABLE 2. Quantitative to Qualitative Mapping.

State	Transition Points
VERY-HIGH	
	70°F
HIGH	
	66°F
NOMINAL	
	58°F
LOW	
	54°F
VERY-LOW	

The rules are not tied to a specific configuration or load status of the EATCS. System state changes due to heat load variation, valve manipulation, or setpoint change may all be part of a normal operating plan. Since the RBS is integrated with the EATCS model described earlier, expected/computed values for a new thermal bus state are used to dynamically change transition point ranges. These new ranges then map incoming sensor data to an appropriate qualitative state. Figure 3 shows a simplified FDIR rule and some of the types of qualitative terminology used.

```
if rfmd-motor-speed is rapidly-decreasing and
    rfmd-end-to-end-deltap is low and
...
then
    ... and
    send-alarm("Evidence of an RFMD motor
failure", medium-priority)
```

Figure 3: The FDIR rules reference qualitative states and trends.

Table-driven systems and traditional rule-based implementations tend to degrade rapidly in the presence of failed sensors. In the TCSAP RBS, if a sensor has been failed by the model-based sensor validation routine the system attempts to automatically use backups. If a sensor that has been failed has a backup, then the backup sensors' reading will be provided for the failed sensors' reading. This allows the FDIR rules to function without change even if the primary sensors they refer to have failed. A backup sensor can be an actual sensor or a calculated value (e.g. a delta pressure calculated by two existing and "good" pressure sensors). If an actual sensor exists that can be used as a backup sensor for another, then the actual sensor is preferred over a calculated value.

Human Interface

The Human Interface (HI) allows the operator to monitor the status of the EATCS hardware and to understand the reasoning behind KBS messages and activities. G2 allows the HI to be built interactively on windows, called workspaces. Note that multiple workspaces may exist on the screen at a time. A workspace called the Schematic Browser allows quick and easy access to different contexts and varying levels of detail. Figure 4 shows the check-box format of the Schematic Browser workspace.

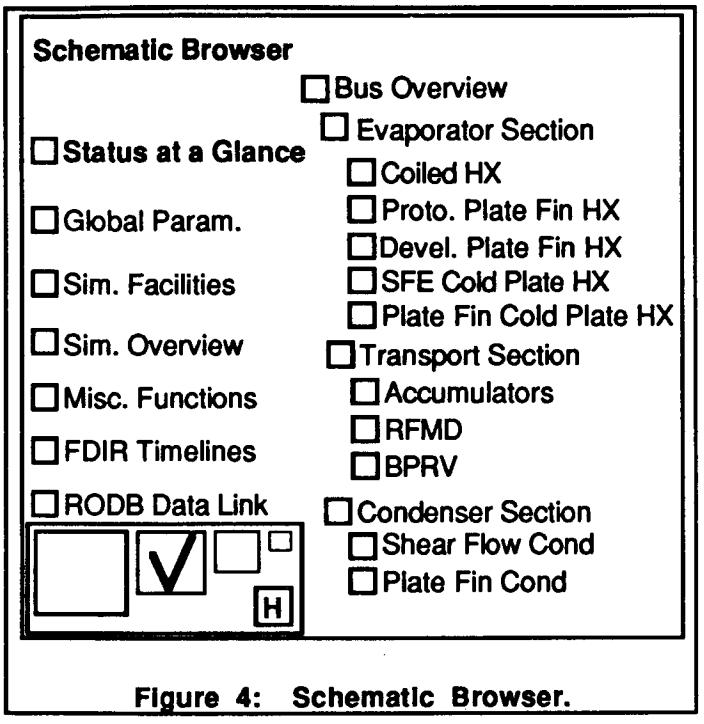

Figure 4: Schematic Browser.

The Status-at-a-Glance workspace (Figure 5) was developed to show the relationships between key values and is generally the most useful for monitoring purposes[9]. Since the EATCS is designed to maintain a constant heat sink temperature for station heat loads, the evaporator liquid supply temperature is a crucial measure of system performance and status. At the top of the screen are the Evaporator and Setpoint/System temperatures. At the bottom of the screen the exit quality and subcooling are used to present high-level evaporator and condenser loop status. The Mass Gauging and RFMD displays in the center show the status of transporting liquid and vapor throughout the system. By normalizing the observations with their expected values, a high or low sensor reading is immediately visible as an extension of its bar chart above or below the normalization (horizontal) line.

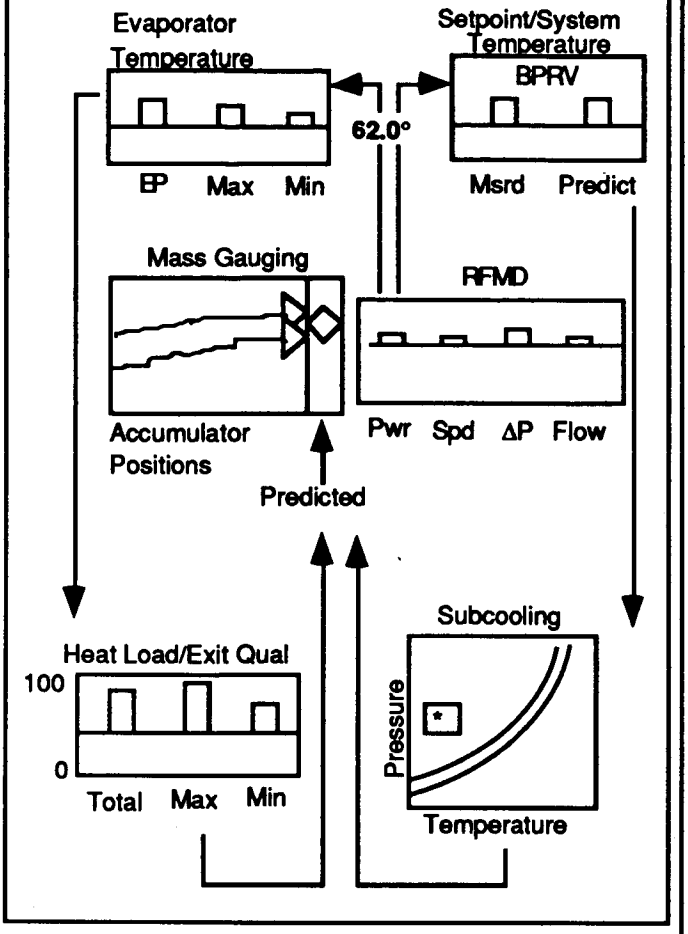

Figure 5: Status at a Glance.

The FDIR Timeline workspace notifies the operator of sensor validation and diagnostic messages (Figure 6). By clearly distinguishing between sensor validation messages, low priority fault messages, medium priority fault messages, and high priority fault messages, the Timeline gives the operator several tools for handling crucial messages and delaying action on lower priority information. In a real-time situation several messages can scroll off the Alarm workspace before the operator has a chance to respond. Each time a message is sent from the KBS to the Human Interface, the corresponding Timeline shows a "Blip". Any messages that might have scrolled off of the Alarm workspace too quickly are still visible as blips on the Timeline. The blips visually represent time-relative placement of each message to the other messages. By selecting the icon beside the desired message timeline, an operator can display messages of that specific priority on a separate workspace. Selection of individual messages allows access to more specific information about the diagnosis. The WHY option on a message displays time histories of sensors, pseudos, and simulated values pertinent to the diagnosis.

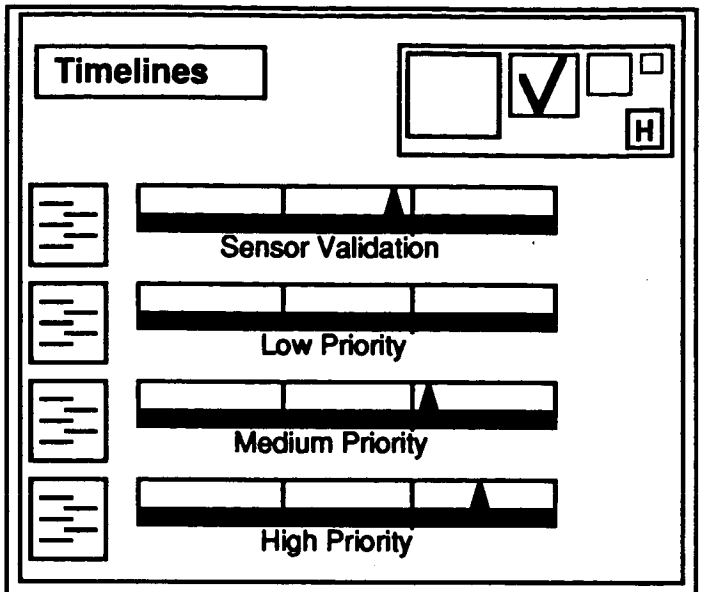

Figure 6: FDIR Timeline.

The second column on the Schematic Browser references workspaces that present a more detailed placement of instrumentation than the Status-at-a-Glance screen. These can be displayed individually as the Evaporator, Transport, and Condenser sections of the bus. They can also be displayed simultaneously using the Bus Overview selection.

The component schematics show the highest level of detail available through the HI. These screens present individual evaporators, condensers, accumulators, the BPRV, the RFMD, and all available instrumentation for each.

The Simulation Facilities and Simulation Overview screens provide a view of the internal KBS model readings. These show exactly where the KBS expects the hardware to be and allow the operator to manually adjust key parameters of the internal simulation.

A sample sequence of actions might begin with a flight controller observing an increase in total quality on the Status-at-a-Glance screen. The controller then displays the Evaporator Section to determine if any or all of the evaporator outlet temperatures are high. Subsequent actions might take the controller directly down to a detailed evaporator schematic or over to view the Transport Section. As the anomaly continues, the KBS issues messages validating the sensors and warning of "Evaporator Blockage" on a single evaporator. This activates an Alarms workspace and brings it to the top of the screen. By now, the controller may have gone to the Simulation Overview screen to compare observed evaporator loop conditions with calculated predictions from the model. Alternatively, the operator might "click" on the warning message and request an explanation of "WHY" the KBS made this diagnosis. In this example, plots of evaporator inlet and outlet temperatures, flow,

and delta-pressures would be presented. Several combinations of these readings could be indicative of some type of blockage.

Summary

Using a combination of conventional programming, rule-based technology, and model-based reasoning, the KBS is able to monitor, control, and perform FDIR on the SSF EATCS. Using an internal simulation model, the KBS can perform sensor validation and component diagnosis by comparing observed sensor readings with their computed values. The qualitative representations mapped by the model and used in the rule-based portion of the system increase flexibility and robustness. The KBS human interface makes use of data in the internal model to focus the controller on areas of inconsistent behavior.

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