Automated System Checkout to Support Predictive Maintenance for the Reusable Launch Vehicle

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ABSTRACT

The Propulsion Checkout and Control System (PCCS) is a predictive maintenance software system. The real-time checkout procedures and diagnostics are designed to detect components that need maintenance based on their condition, rather than using more conventional approaches such as scheduled or reliability centered maintenance. Predictive maintenance can reduce turn-around time and cost and increase safety as compared to conventional maintenance approaches. Real-time sensor validation, limit checking, statistical anomaly detection, and failure prediction based on simulation models are employed. Multi-signal models, useful for testability analysis during system design, are used during the operational phase to detect and isolate degraded or failed components. The TEAMS-RT real-time diagnostic engine was developed to utilize the multi-signal models by Qualtech Systems, Inc.

Capability of predicting the maintenance condition was successfully demonstrated with a variety of data, from simulation to actual operation on the Integrated Propulsion Technology Demonstrator (IPTD) at Marshall Space Flight Center (MSFC). Playback of IPTD valve actuations for feature recognition updates identified an otherwise undetectable Main Propulsion System 12 inch prevalve degradation. The algorithms were loaded into the Propulsion Checkout and Control System for further development and are the first known application of predictive Integrated Vehicle Health Management to an operational cryogenic testbed. The software performed successfully in real-time, meeting the required performance goal of 1 second cycle time.

1. PROJECT DESCRIPTION

1.1 IPTD Overview

The Systems Health Management Group from Ames Research Center (ARC), Code IC, participated on a product development team led by Rockwell Space Systems Division (now Boeing North American) during Phase 1 of the X-33 program for the Integrated Propulsion Technology Demonstrator located at MSFC. NASA team members included MSFC (test article integration and test operations), ARC (onboard diagnostic/prognostic algorithms and fault isolation models) and Lewis Research Center (LeRC) (smart sensor algorithms). The IPTD objective was to evaluate and predict ground and flight propulsion operations improvements which reduce turn-around-time and operations costs risk.

1.2 PCCS Overview

The PCCS controls the X-33 Main Propulsion System (MPS) type components on the IPTD and monitors hundreds of measurements from the associated sensors. The PCCS consists of nine modules: 1) the Task Wrapper, 2) the Task Manager, 3) Sensor Validation, 4) System Transient Detector, 5) Sensor Reconstruction, 6) Feature and Level Detection with Prognostics and Limit Checking, 7) Valve Function and Sensor Validation, 8) Failure Isolation (TEAMS-RT[1]), and 9) Significant Event Record (SER) Generator. The software runs on a SPARC 20 workstation. ARC developed modules 2, 6, 7, and 9 and integrated them with modules 3, 4, and 5 from LeRC and module 8 from Qualtech Systems, Inc. The Task Manager interfaces with the Task Wrapper, developed at Rockwell, which provides the interfaces to the test stand. A top level view of these modules is shown in Figure 1.

There were 3 major goals in this task:

1) Verification of Reusable Launch Vehicle (RLV) on-board propulsion prognostic and diagnostic algorithms on the IPTD.
2) Demonstration of the use of design models in real-time system monitoring and fault isolation.
3) Demonstration of real-time performance of PCCS on IPTD to reduce the risk of deploying such a system for actual operations.

[1] The Testability Engineering and Maintenance System – Real-time (TEAMS-RT) is available from Qualtech Systems Inc., 66 Davis Road, Storrs, CT 06268 at www.teamqsi.com.

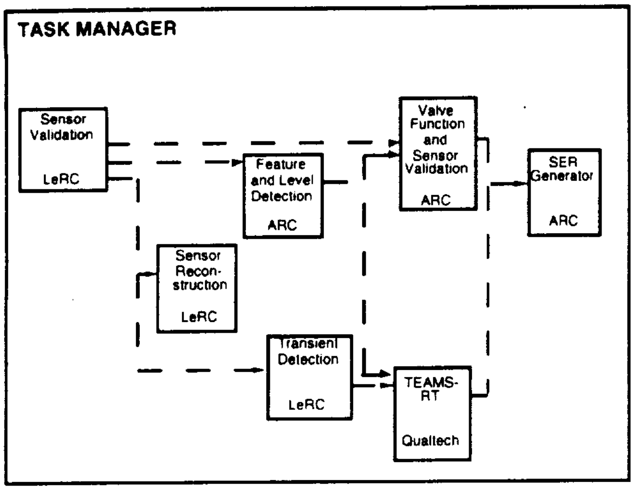

Figure 1: PCCS Top Level Architecture Over iew

The following sections describe the software architecture of the PCCS and the results of the IPTD test stand demonstrations that occurred at the end of this task.

2. PCCS ARCHITECTURE

2.1 Architecture Overview

A brief description of the eight software modules developed or integrated by ARC follows:

1) Task Manager - controls the sequencing of the analysis modules.
2) Sensor Validation - detects sensor failures.
3) System Transient Detector - detects transient features which occur during periods of steady operation and which are not attributed to sensor failure or normal system operation.
4) Sensor Reconstruction - calculates a replacement value for a failed sensor based on models and on the values of nominal sensors.
5) Feature and Level Detection with Prognostics and Limit Checking - detects features and measured levels in the signals acquired from sensors on the mechanical components, predicts the future values of the features and levels, checks the current and future values of the features and levels against pre-defined limits, and flags maintenance and failure warnings.
6) Valve Function and Sensor Validation - determines which system sensors have changed their status to failed or reconstructed.
7) TEAMS-RT - uses model-based reasoning to determine the location of components which have failed or need maintenance using feature and level information.
8) Significant Event Record Generator - produces the SERs to be used for determining maintenance actions.

2.2 ARC Module Overviews

2.2.1 Task Manager (TM)

The Task Manager interfaces to the Task Wrapper, and hence, the teststand, and passes along sensor data and status from the Task Wrapper to the other modules. The Task Manager controls the sequencing of the analysis modules and outputs sensor and valve status and Significant Event Records to the Task Wrapper which then displays appropriate status messages to the operator.

2.2.2 Feature and Level Detection with Prognostics and Limit Checking (FLDPLC)

The Feature and Level Detection module detects features and measures levels in the signals acquired from sensors on the mechanical components, predicts the future value of the features and levels, checks the current and future values against predefined limits, and flags maintenance and failure warnings. Depending on the mode of the PCCS, certain sensor values are used to infer more information about some particular component of the system. A group of sensor values is used to determine a feature. A feature may be peaks, rise time, fall time, etc. of a wave form. This feature is then compared to predefined limits. If it is out of bounds a failure warning is issued. The result is also used to predict when a limit may be reached in the future. A maintenance warning is issued if the limit is likely to be reached within a prescribed time interval.

2.2.3 Valve Function and Sensor Validation (VFSV)

The Valve Function and Sensor Validation module determines which system sensors have changed their status to failed or reconstructed and outputs a list of the changed sensors. System sensor status is determined outside of this module. VFSV sends results of its sensor status continuity analysis to the SER Generator.

2.2.4 Significant Event Record Generator (SERG)

The Significant Event Record Generator creates SERs from the results of the analysis modules, FLDPLC, TEAMS-RT, SV, and VFSV. These SERs are used by Informed Maintenance (IM) modules for determining required maintenance actions.

2.3 ARC Input File Descriptions

Many of the input files utilized by these modules are developed at Rockwell and delivered to ARC as a Microsoft Excel workbook. The individual sheets are then reformated as text files. The information in these files is used to establish the appropriate system configuration according to the current phase, function, and command from the test stand.

2.4 Qualtech Module: TEAMS-RT

The TEAMS-RT module implements a model based reasoning approach, wherein information about failure sources, tests and monitoring points, redundancy and system modes are captured in colored directed graph models known as multi-signal models [1,2]. In simple terms, these models enable the inference engine to interpret test results by answering these questions: given a test T1, which components can cause it to fail; or, if the health of component C1 needs to be checked, which tests observe C1. Such models may be automatically generated via fault simulation (using simulators such as Saber, PSpice [3], $MATRIX_X$ or VHDL simulators) or entered manually in TEAMS, the model development tool, based on an engineering understanding of the system or legacy data captured in FMECA reports, fault trees, CAD data, and technical documentation. The same model is then used by TEAMS-RT for real-time monitoring, thus ensuring that the results predicted in the design stage by TEAMS are indeed achieved in actual application. In our case, the multi-signal models were created in TEAMS at Rockwell.

The objective of the TEAMS-RT inference engine is to associate four distinct (failure) states with each component in the system: (1) *Good*, (2) *Bad*, (3) *Suspected*, and (4) *Unknown*. In addition, results of prognostics checking (see Section 2.2.2) were used to diagnose components that were *Suspected to be in need of maintenance* and *Definitely in need of maintenance*. TEAMS-RT also has additional capabilities of handling dynamic system mode changes, and diagnosis and prognosis in fault-tolerant systems with built-in redundancy. Some unique features of TEAMS-RT are:

(i) efficient real-time processing of sensor results;

(ii) update of fault-test point dependencies in response to system mode changes;

(iii) update of dependencies resulting from failures in redundant components;

(iv) and detection and isolation of multiple simultaneous failures.

The TEAMS-RT algorithms developed for the IPTD demonstration were extensively tested in a simulation environment. Multiple faults were seeded in randomly generated models. These models were then exercised in different modes of operation and pass/fail results of tests were fed to TEAMS-RT. Table 1 presents simulation results for TEAMS-RT on a 1000x1000 system with 80 modes of operation. Column 1 lists the number of faults inserted. |Tp| is the number of tests that passed in spite of the failures. The remaining columns list the number of components that were declared to be good, bad and suspected (residual ambiguity) by TEAMS-RT, and the processing time. Thus, the simulation results indicated that TEAMS-RT will easily satisfy the design goal of processing 1000 test results in under 200 msec.

3. MSFC TESTS AND RESULTS

3.1 Test Description

The Informed Maintenance demonstration tests were conducted on the Integrated Propulsion Technology Demonstrator at MSFC. The propulsion module of the IPTD consists of propulsion system hardware and the Propulsion Checkout and Control System. The propulsion hardware components are integrated within a structural support fixture which includes mounting provisions for the system feed lines, liquid oxygen (LO_2) and hydrogen (LH_2) tanks, vents, and multiple valves. The system is installed in the MSFC Advanced Engine Test Facility (AETF). The PCCS provides the hardware and supporting software to checkout and control the IPTD. The hardware includes a smart controller, multiple sensors, and data acquisition system. The software provides signal processing, data analysis, automated reasoning, and decision making. Sensor data flows to the software once per second, which establishes the performance requirement for the software system of 1 second cycles.

Table 1: Performance results of TEAMS-RT for simulated system with 1000 faults and tests.

faults	|Tp|	Good	Bad	Suspect	time(ms)
1	**993**	**997**	**1**	**2**	**50**
2	**978**	**996**	**2**	**2**	**50**
5	**931**	**991**	**5**	**4**	**50**
10	**881**	**983**	**10**	**7**	**75**
20	**819**	**973**	**20**	**7**	**87**

The mechanical components of the IPTD are monitored via the sensors. These may include observations of temperature, pressure, electrical current, or other physical phenomena. Information from the sensors is digitized into time series data. The data are processed via selected signal processing and conditioning algorithms to extract features of interest. The automated reasoning and decision software, TEAMS-RT, is used for system fault diagnosis.

The IM demonstration tests were performed during a two month period, from late March to May 1996. At the beginning, the hardware was integrated and was checked out by data acquisition software. The digitized sensor data for each test case were saved in data files, then the data files were processed and analyzed off-line. Using data from many test cases, it was determined that the hardware was integrated properly and all parts of the software were working correctly. There were three types of software tests: 1) tests with data of natural degradation, 2) tests with data of injected degradation, and 3) tests with simulation data. In the final week of testing, the full PCCS software system was tested with live data. These tests are described in detail in the following section.

3.2 Test Results

3.2.1 Tests with Data from Natural Component Degradation

During the test stand operations, PV202, a prevalve, showed a natural degradation in performance and slammed on a valve closing operation. Pressure signature patterns for the valve as the valve degraded are shown in Figures 2 and 3. When data prior to the slamming were input to the software, it computed several features. The FLDPLC correctly predicted that the initial actuation pressure value would be outside the nominal range within the next 4 valve closing operations (Figure 4), and recommended maintenance for the valve.

3.2.2 Tests with Data of Injected Degradation

In the last week of the test period (May 20 - May 24), the software and hardware were integrated and several automated tests were performed with everything operational in real-time at MSFC AETF.

According to the IM test plan, eight test cases were performed. The results of two test cases are reported here.

3.2.2.1 Basic Test

Test Description:

Cycle PV201 (PreValve), PV203 (SpringValve), and PV204 (SpringValve) five times in O2_PRE_TEST phase without any changes or adjustments.

The test results showed that the software had been integrated properly. The computer running time for data acquisition, signal processing, and feature extraction was less than 10% of the requirement. The baseline measurements of features were obtained, and the fact that there was negligible difference between different measurements for the same features showed that the PCCS was stable and accurate.

3.2.2.2 Fault Injection Test on PV203 in O2_PRE_TEST Phase.

Test Description:

Cycle PV203 while adjusting the needle valve from a healthy PV203 operation until a failure event is generated. This is to see if the orifice gets flagged as the bad component.

The test results showed that the actuation time and the total transition time for the Spring Valve were getting longer as the needle valve was adjusted to simulate more clogging, as expected. The software predicted a failed component, the orifice, and asked for maintenance for the valve. The values of the corresponding transition times and actuation transition times computed in the FLDPLC are summarized in Table 2.

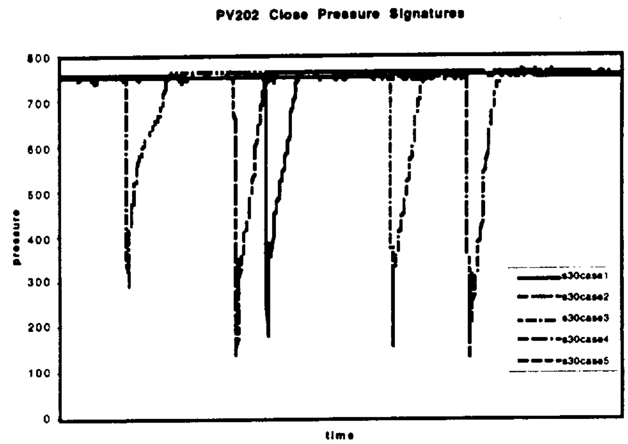

Figure 2: PV202 Close Pressure Signatures

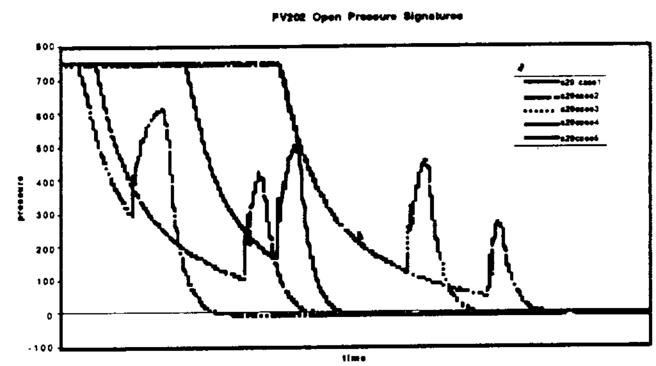

Figure 3: PV202 Open Pressure Signatures

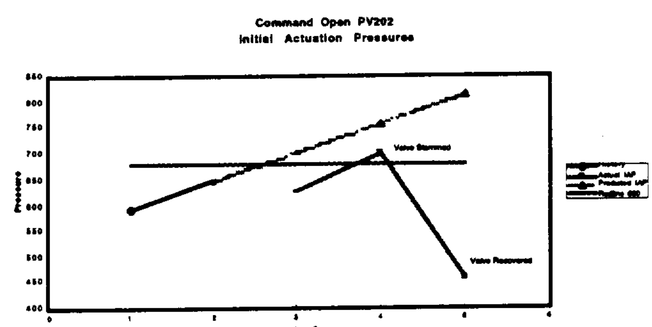

Figure 4: PV202 Maintenance Recommendation

Table 2: Summary of Feature Values for PV 203 Tests

PV 203 Test	Transition Time (sec)	Actuation Transition Time (sec)
pv203_31_good	3.06	0.9
pv203_31_5t	7.52	2.26
pv203_31_3t	10.14	3.12
pv203_31_2t	16.44	5.24

3.2.3 Tests with Simulation Data

$MATRIX_X$[2] simulation models were available for the pre-valve, spring valve and solenoid valve. Simulation runs were used to understand the behavior of components. In the case of the prevalve, simulation runs were used to decide which features would be diagnostic of which degradations. Prevalve simulation data were also used to test the software before testing on the MSFC test stand.

3.2.4 Tests of the TEAMS-RT Diagnostic Capability

The multi-signal model of the IPTD was developed in two stages. First, the basic topology of the teststand components was modeled. Valves that controlled propellant flow were isolated as the major functions. Components that control or support these valves were grouped with the valve. Signals were associated with each valve and then tests were defined for the signals. Flow characteristics were then modeled for a cryogenic valve. This model included temperature, pressure, and flow rate, in both the forward and backward directions for each operating mode of the valve. Tests were added for the system parameters, temperature and pressure transients, based on what measurements were available on the test stand.

Once the multi-signal model was constructed, the model was placed in different operational modes and tests were selected for different operational modes. The propagation of signals was checked to see if the dependency relationships were properly defined. The real-time system test did not proceed as easily, however. Fault isolation software could not be fully tested because there were basic errors made in labeling the nodes in the model, which lead to misdiagnosis. It was not possible to rectify the model for the tests with live data from the IPTD within the allocated week of test time. Our recommendation is for earlier completion of the TEAMS models so that checkout could occur with simulation or off-line test stand data, enabling obvious modeling errors to be corrected. It is expected that the basic models would also need later revisions as behavior of the interactions of components is better understood from observing system operation.

[2] $MATRIX_X$ is available from Integrated Systems, Inc., 201 Moffett Park Dr., Sunnyvale, CA 95054-3309, phone (408) 542-1575.

4. SUMMARY AND CONCLUSIONS

In summary, PCCS software modules were tested with a variety of data, from simulation to actual operation on the Integrated Propulsion Technology Demonstrator at MSFC. Capability of predicting the maintenance condition was successfully demonstrated with all data. Playback of IPTD valve actuations for feature recognition updates identified an otherwise undetectable Main Propulsion System 12 inch prevalve degradation. The algorithms have been loaded into the IPTD for further development and are the first known application of predictive Integrated Vehicle Health Management to an operational cryogenic testbed. The software performed successfully in real-time, meeting the required performance goal of 1 second cycle time.

5. REFERENCES

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