DIAGNOSTIC DIGITAL THREAD

ENSURING PHM & CBM EFFECTIVENESS

(TECHNICAL NOTES)

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DSI INTERNATIONAL, INC.

DIAGNOSTIC DIGITAL THREAD

AI through Diagnostics Engineering

Ensuring PHM & CBM Effectiveness

Using

Prognostics-Informed Diagnostics

- **Prioritizing the Role of Diagnostics Engineering – with the Diagnostic Digital Thread:**
  - Determine, enrich and manage the capability, role and limitations of any maintenance objectives.
  - Establish the functional and failure interrelationships throughout all hierarchical levels of the design.
  - Validate all potential assertions premised on any implied level of capability of Failure Detection or Fault Isolation (FD/FI), and/or any precursors thereto, in the producing of any independent or interdependent design assessment product during or after the Design Development Lifecycle.
  - Validate the operational and support capability of the diagnostics for any constraints as transferred to any specified Sustainment paradigm. This may also include the insertion of any defined PHM capabilities.
  - Determine the inherent and potential inference(s) of "Isolation" within the context of the integrated system(s) in the producing of a "common thread", which at its core, is the function of the intelligent ***eXpress*** model – interconnecting each design and Sustainment discipline, regardless of Maintenance philosophy.
  - Assimilate and integrate any applicable data used in the forming of, or as an output generated from, any interdisciplinary design assessment product(s) – integral in the establishing of an *intelligent integrated knowledgebase "asset"* in the form of an ***eXpress*** System model. As such, the establishing of this *intelligent asset* shall be a prerequisite for the forming of any desired elite-level, Sustainment solution(s).
  - Enable design assessments (Testability, Reliability, Safety, and Maintainability) to be "turn-key" outputs from the evolving design *AI asset* throughout the entire Product Lifecycle, including the inclusion and impact of design updates or modifications.
  - Provide a Diagnostic Digital Thread as a collaborative interdisciplinary and Model-based Systems Engineering (MBSE) function throughout the Design Development process.
  - Balance and validate any proposed sustaining approaches, including PHM, PdM, RCM or corrective maintenance versus any dependent predictive, mitigating or corrective actions based thereon, over the Sustainment Lifecycle by this *AI asset.*

- **Fault Detection vs. Fault Isolation:**
  - **Fault Detection**, ***FD***, identifies the existence of any possible failure(s), whereby **Fault Isolation**, ***FI***, identifies the Fault Group(s) or component(s) that is considered to contain the failure(s).
  - **FD**, as identified in the table below, is used to infer a capability in the assessment product(s) of any design disciplines or to form input targeting sustainment objectives (Reliability, Availability, Maintainability, etc..;
  - **FI**, as identified in the table below, is essentially absent from each design discipline – except Diagnostics Engineering - yet **FD**/**FI** is expected to be partially or fully performed in any Sustainment paradigm.

Optional & ***Independent*** Role(s) of PHM or CBM in the Product Lifecycle

Design Development (Disciplines, Standards & Methods)		Without the Diagnostic Digital Thread	**Sustainment** (Environment / Tools & Methods)
Systems Engineering (INCOSE)	SysML PLM MBSE / MBSA	**FI missing?** Typically, Discreet activities **Fault Isolation** Not effectively integrated into Sustainment activities	
Reliability Engineering (RAMS, SIL)	FD FMEA FMECA RCM, CBM, MTBF/FR HALT / HASS / AST		**Production** FD/FI, ATE, RTF, Manual Embedded Diagnostics
Safety Engineering (RAMS, ARP, SIL)	FHA, CC FTA MBSA Sneak Path Analysis Airworthiness FD		**Depot Level / Repair Lab** FD/FI, ATE, RTF, RCM, CBM, BIT, Manual PMA: Static/Dynamic Diagnostic Reasoning
Health Management (IEEE, PHM Society)	FD HM PHM, CBM Sensors IVHM ISHM		**Health Monitoring** FD, BIT, CBM, HM Fault Codes, Sensors Embedded Diagnostics Airworthiness (Air)
TEST Engineering (IEEE, MIL, SIL)	DFT, JTAG, FD ATE / ATS Detection, BIT Test Validation Test/Fault Coverage	**PHM/CBM** Discreet activities **PHM** Typically, Not effectively integrated into Sustainment activities	**Health Management** FD, BIT, Sensors, Fault Codes Embedded Diagnostics Static/Dynamic Diagnostic Reasoning IVHM, ILS, CBM, PHM, ILS, ALIS/ODIN
Diagnostics Engineering (IEEE, RAM-T)	DFT, JTAG, FA, FD/FI RCM, CBM, HM, RTF Fault Codes, TRD/TPS Test/Diag. Validation Static/Dynamic Reasoning Embedded Diagnostics		**Intermediate Level** FD/FI, Fault Codes, Spares, Troubleshooting ATE, PMA, ATS, RTF, CBM, RCM, ALIS/ODIN PMA: Static/Dynamic Diagnostic Reasoning
Maintainability Engineering (RAMS)	MTTR, LORA TRD / TPS RCM, CBM, RTF Fault Codes PMA (w/Empirical) FD		**Operational Level** FD/FI, Fault Codes, Spares, Troubleshooting ATE, PMA, ATS, RTF, CBM, RCM, ALIS/ODIN PMA: Static/Dynamic Diagnostic Reasoning
Logistics Engineering (RAMS, SOLE)	FD RCM, CBM ILS / PBL ATS, ALIS/ODIN PMA , Spares		**PLM Complex Maintenance** Any/all forms described above

- **PHM and/or CBM in Design – without the Digital Thread:**
  - Typically performed as *independent* or *competing* activities.
  - Not typically worked as a collaborative activity as determined through robust Diagnostics Engineering practices.
  - Effectiveness is constrained to the robustness of the Diagnostics Engineering practice.
  - Are dismissive of new PLM, MBSE or MBSA processes unless fully integrated within Asset-Level or Systems Diagnostics Engineering.

- **PHM and/or CBM in Sustainment – Expanding into the ATE Environments?**

As Industry is exploring the insertion of CBM into the ATE or ATS solution, as is already the case for PHM when inserted into on-board vehicle Health Management applications, neither specific application is able to fully consider the overall test coverage of any "test" (on-board BIT or as performed by ATE) when performed as an independent activity.

As many complex designs are integrated into (and updated repeatedly over the product lifecycle) the interdependent Integrated Systems design, the flow of highly complex functional and failure propagations shift and move through and around these subsystem designs, which pose an ever increasing risk for human error when trying to perform "health reasoning" without considering these propagations in entirety.

The task to consider these variables when designing on-board PHM (Diagnostic Reasoning) systems becomes daunting when expected to account for the variable (on-board) BIT test coverages when vehicle operational modes alter the certainty of sensor data depending on when retrieved by the BIT.

As operational modes and environmental conditions evolve as expected or as unexpected, diagnostic or "Health Reasoning" certainty is always *dependent* and *interdependent* upon the accuracy and coverage of the BIT and/or sensors as designed for PHM. Alternatively, fully defining the limitations and constraints of the Test Coverage (throughout the design hierarchy), will provide certainty of the Test Coverage as reported by the on-board BIT and achieve a higher level of diagnostic accuracy.

PHM and/or any CBM application should be performed as an interdisciplinary, interdependent, and evolving activity. The Diagnostic Digital Thread provides a natural link to capture, facilitate and integrate all of the aspects of a complex design that need to be fully considered when attempting to devise a sustainment practice that fully matches the inherent and operational capabilities of the design. The expert knowledge is no longer a perishable consequence as maintenance and design updates are performed.

- **Preparedness for the Impact of design updates – Establishing an "AI asset"**

Acquisition vs. Sustainment budgets are not typically equitable, nor certain. To mitigate the severity of these challenges, all of the functional and failure propagations are forever captured in the *eXpress* model and any updates to the design are easily integrated into this living *AI asset*, in essence, a *Digital Twin*.

By allowing *eXpress* to restructure and reorganize design changes, it will determine the impact to the Test Coverage as described within the Integrated Systems design. This will enable evolving assessments to be (re)generated reflecting any new constraints with the diagnostics or the proposed PHM capability. The captured expert knowledgebase, or AI Asset, can welcome and integrate design updates before exporting "cooked" data into a form for immediate deployment into the Sustainment paradigm.

Interdependent Role(s) of Elite Diagnostics Engineering in the Product Lifecycle

Design Development (Disciplines, Standards & Methods)		With the Diagnostic Digital Thread	**Sustainment** (Environment / Tools & Methods)
Systems Engineering (INCOSE)	SysML PLM MBSE / MBSA	**Fault Isolation** effectively integrated to Design & Sustainment activities.	
Reliability Engineering (RAMS, SIL)	FD FMEA FMECA RCM, CBM, MTBF/FR HALT / HASS / AST		**Production** FD/FI, ATE, RTF, Manual Embedded Diagnostics
Safety Engineering (RAMS, ARP, SIL)	FHA, CCA FTA MBSA Sneak Path Analysis Airworthiness FD		**Depot Level / Repair Lab** FD/FI, ATE, RTF, RCM, CBM, BIT, Manual PMA: Static/Dynamic Diagnostic Reasoning
Health Management (IEEE, PHM Society)	FD HM PHM, CBM Sensors IVHM ISHM	**AI Diagnostic**	**Health Monitoring** FD/FI, BIT, CBM, HM Fault Codes, Sensors Embedded Diagnostics Airworthiness (Air)
TEST Engineering (IEEE, MIL, SIL)	DFT, JTAG, FD ATE / ATS Detection, BIT Test Validation Test/Fault Coverage	**Digital Thread**	**Health Management** FD/FI, BIT, Sensors, Fault Codes Embedded Diagnostics Static/Dynamic Diagnostic Reasoning IVHM, ILS, CBM, PHM, ALIS/ODIN
Diagnostics Engineering (IEEE, RAM-T)	DFT, JTAG, FA, FD/FI RCM, CBM, HM, RTF Fault Codes, TRD/TPS Test/Diag. Validation Static/Dynamic Reasoning Embedded Diagnostics	**CBM/PHM** effectively integrated into Sustainment activities.	**Intermediate Level** FD/FI, Fault Codes, Spares, Troubleshooting ATE, PMA, ATS, RTF, CBM, RCM, ALIS/ODIN PMA: Static/Dynamic Diagnostic Reasoning
Maintainability Engineering (R&M or RAMS)	MTTR, LORA TRD / TPS RCM, CBM, RTF Fault Codes PMA (w/Empirical) FD		**Operational Level** FD/FI, Fault Codes, Spares, Troubleshooting ATE, PMA, ATS, RTF, CBM, RCM, ALIS/ODIN PMA: Static/Dynamic Diagnostic Reasoning
Logistics Engineering (RAMS)	FD RCM, CBM ILS / PBL ATS, ALIS/ODIN PMA , Spares		**PLM Complex Maintenance** Any/all forms described above

Common Disciplinary Acronyms				
AI	Artificial Intelligence		ILS	Integrated Logistics Support
ALIS	Autonomic Logistics Information System		INCOSE	International Council on Systems Engineering
ARP	Aerospace Recommended Practice		ISHM	Integrated Systems Health Management
AST	Accelerated Stress Testing		IVHM	Integrated Vehicle Health Management
ATE	Automatic Test Equipment		JTAG	Joint Test Action Group
ATS	Automatic Test System/Solution		LORA	Level Of Repair Analysis
BIT	Built-In Test		MBSA	Model-Based Safety Analysis
CBM	Condition-Based Maintenance		MBSE	Model-Based Systems Engineering
CCA	Common Cause Analysis		MTBF	Meat Time Between Failure
DFT	Design For Test; Design For Testability		MTTR	Mean Time To Replace
FA	False Alarms		ODIN	Operational Data Integrated Network
FD	Fault Detection		PBL	Performance-Based Logistics
FI	Fault Isolation		PLM	Product Lifecycle Management
FD/FI	Fault Detection and Fault Isolation		PMA	Portable Maintenance Aid
FHA	Functional Hazard Analysis		PHM	Prognostics Health Management
FMEA	Failure Modes Analysis		R&M	Reliability and Maintainability
FMECA	Failure Modes and Criticality Analysis		RAMS	Reliability, Availability, Maintainability, Safety
FR	Failure Rate		RCM	Reliability-Centered Maintenance
HALT	Highly Accelerated Life Testing		RTF	Run-To-Failure
HASS	Highly Accelerated Stress Screening		SIL	Safety Integrity Level
HM	Health Monitoring/Management		TRD	Test Requirements Document
IEEE	Institute of Electrical and Electronic Engineers		TPS	Test Program Set

- **Prognostics-Informed Diagnostics integral to PHM or CBM activities:**

  - For any complex or critical system, PHM and/or CBM design activities must be performed within the context of an equally robust Diagnostic Engineering design development process. This will enable these activities to capture and extend the utility of valuable expert knowledge for a myriad of future purposes. This is a uniquely exceptional capability inherent within the *eXpress* Diagnostic modeling in its establishing of a *Digital Thread* environment. It is also essential in mitigating the inevitability of losing sustainment effectiveness without otherwise, locking-in of this expert knowledge – in perpetuity.

  - The disclosure of the limitations of PHM or CBM is conditioned upon the Integration of the data products produced by and between the design disciplines from within a highly collaborative development process. These design assessment products are produced merely as design instantiations, or "Diagnostic Studies" that are accessible at any time throughout the design development process, or upon the inclusion of any design updates during the sustainment lifecycle. This allows the AI asset to produce a fluid and intelligent repository of expert knowledge as integrated with their interrelated role(s), and respective of the limitations of the Sustainment capability throughout the System and Product Lifecycle.

  - The Diagnostic Digital Thread is not a luxury nor is it expendable, but rather it is what defines and ensures the constraints and effectiveness of any proposed Operational or Sustainment ambitions. It accomplishes this by creating a new and irreplaceable integrated AI Asset that forever retains the expert knowledge to assess, support, maintain, new or legacy designs and variants therefrom, well into the future.