A Standard for Prognostics and Health Management in the Context of Automatic Test Systems

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***Abstract*—In 2019, the Institute for Electrical and Electronics Engineers (IEEE) approved a new P2848 standards development project, titled "Standard for Prognostics and Health Management in Automatic Test Systems." The working group seeks to develop a new standard that addresses the unique data acquired from ground-based support equipment, in particular Automatic Test Systems, to enable improved decision making in Condition Based Maintenance of electronic systems. As a core approach, the P2848 working group has been working to identify key data items defined by existing standards that would enable maintenance and support personnel achieve these goals. This paper will review the overall approach and current progress in the development of this standard and discuss its use in the context of a larger Conditional Based Maintenance (CBM) environment.**

I. Introduction

In 2019, the Institute for Electrical and Electronics Engineers (IEEE) approved a Project Authorization Request (PAR) for a new standard on prognostics and health management (PHM). The P2848 standards project is titled "Standard for Prognostics and Health Management in Automatic Test Systems" and is being developed by a group of over 20 professionals drawn from industry, government, and academia with the goal of advancing data standards to support PHM-related processes in an ATS environment. The scope of the project reads, "The Prognostics and Health Management – Automatic Test Systems (PHM-ATS) standard provides formal specifications supporting prognostics and health management of automatic test systems as well as units tested by ATS. These specifications focus on the data, services, and processes for determining current and emerging state of health of electronic components and systems in the ATS and units under test (UUTs). Where applicable, this standard utilizes existing condition-based maintenance and PHM-related standards as well as existing UUT and ATS-related information exchange standards." With this scope in mind, the P2848 working group has been endeavoring to identify key data items based on existing standards that can be brought together to achieve the goals embodied in this scope. Rather than reinvent the wheel, the working group is drawing upon and mapping to data elements in the IEEE 1671 Automatic Test Markup Language (ATML) [1], IEEE 1636 Software Interface for Maintenance Information Collection and Analysis (SIMICA) [2], and IEEE 1232 Artificial Intelligence Exchange and Service Tie to All Test Environments (AI-ESTATE) [3] standards. The intent is for this mapping to define the initial specification and provide the basis for creating PHM-based applications and processes in the ATS environment. This paper will review the overall approach and current progress in the development of this standard and discuss its use in the context of a larger Conditional Based Maintenance (CBM) environment.

II. Prognostics and Health Management

These days, considerable writing has been done in the area of Prognostics and Health Management (PHM), yet there is still little agreement about what the term actually means. For purposes of the P2848 standard, we consider that *data* required to support PHM and largely leave the definition of what constitutes PHM to those using the standard. Even so, there are some basic concepts that we would regard as consistent across the field.

Without going through the complete litany of definitions for PHM, we point out one definition that fits the vision of the P2848 standard relatively well. Liu *et al.* state that "Prognostic and Health Management (PHM) systems support aircraft maintenance through the provision of diagnostic and prognostic capabilities, leveraging the increased availability of sensor data on modern aircraft. Diagnostics provide the functionalities of failure detection and isolation, whereas prognostics can predict the remaining useful life (RUL) of the system [4]." We note that the focus of P2848 is on *offboard* processes, rather than relying entirely on sensors onboard a system. In particular, we consider the PHM process from the perspective of an Automatic Test System (ATS), which is discussed in more detail in Section III. We also assert that the standard supports systems other than on aircraft.

Supporting the above, the standard asserts that there is an intrinsic relationship between diagnostics (which corresponds to health assessment) and prognostics (which focuses on health prediction). From this, we posit a data processing pipeline of the form depicted in Figure 1. This pipeline breaks the PHM process down into five distinct phases once a unit under test (UUT) is mounted on the ATS.

1) Monitor: The ATS is designed to test the UUT, and those tests capture data about the state or condition of the UUT.

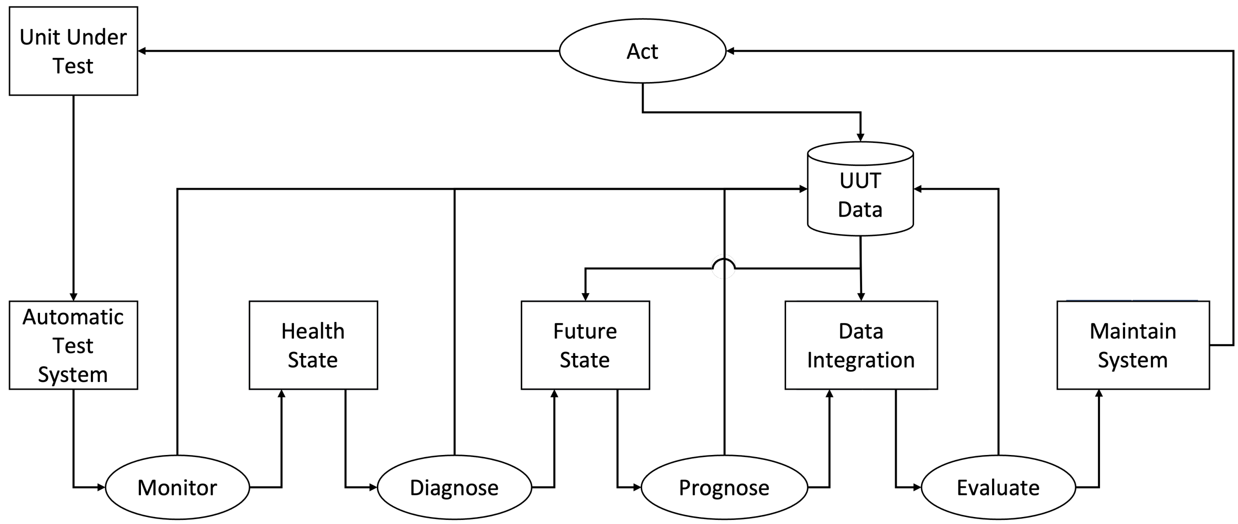

Fig. 1. An ATS-based PHM Pipeline.

2) Diagnosis: Based on the health state information collected from monitoring, any faults in the system are isolated through some diagnostic process.
3) Prognose: Distinct from traditional ATS-based processes that employ a test program to diagnose or verify alone, this standard suggests additional information can be collected based on test results and historical maintenance data to assess possible degraded states and predict how these states might continue to evolve.
4) Evaluate: A potentially new perspective that draws from the strong ties to military maintenance is that the projected health state is then evaluated based on the risks associated with future failure and potential impacts on future missions.
5) Act: Based on risk analysis and consideration of how additional maintenance might mitigate such risks, personnel can make informed decisions on what additional maintenance actions to perform.

III. AUTOMATIC TEST SYSTEMS

Within the Department of Defense (and other organizations), the purpose of an ATS is to test the functionality of a UUT and to detect and isolate failures of components of the UUT. In the context of the P2828 standard, we also acknowledge that an ATS can itself be a UUT; thus, it can perform testing on itself and its components, thereby detecting and isolating ATS failures as well. An ATS consists of a set of computer-controlled instruments capable of generating stimuli and measuring their response to perform tests. The results of the tests are then evaluated in relation to associated UUT functionality and performance as the primary means of determining when and where failures have occurred. This is illustrated in Figure 2.

An ATS automates traditionally manual electronic test processes. Of particular importance for the standard, an ATS is a computer-based, data-driven system that acquires, processes, saves, distributes, and uses test and measurement data. Of note here is that not all ATS use the same software and measurement/stimulus instruments; these configurations vary depending on the level of maintenance, UUT, and the parameters requiring measurement. This naturally leads to the need to standardize the data in a way that varying processes and tools can use the data consistently and reliably.

In the context of PHM (see Section II, the objective goes beyond simply sharing test and measurement data. Data and information need to be collected and integrated from multiple levels of maintenance to best understand the UUT's health status, mission readiness, and maintenance and repair needs. Sharing maintenance information and repair process information such as decision-making, guidance, and expert knowledge enables understanding the complete health status for the operational and maintenance organizations. Consequently, the standard should facilitate analyzing ATS status, test, environmental, and design information to form a knowledge model that directly guides the ATS maintenance and maintenance decision, and maintenance operations. One such knowledge model is depicted in Figure 3.

Details of this model will be discussed in the standard, but to summarize, central to the knowledge model is recognition that multiple data and information sources are required: information specific to the ATS, information drawn from maintenance history, and information drawn from the ATS testing the UUT relative to potential faults of the UUT. Decisions are made based on diagnostic results, prognostic analysis, and mission needs to support the maintenance of the UUT.

IV. CONDITION BASED MAINTENANCE

Within modern maintenance processes in the DoD, considerable attention is being given to CBM. One definition of CBM from the Society of Automotive Engineers (SAE) is "an approach to maintenance whereby maintenance is only performed on evidence of need identified through direct or indirect monitoring. CBM requires specific knowledge of an asset's condition at any given time in its operating life such that

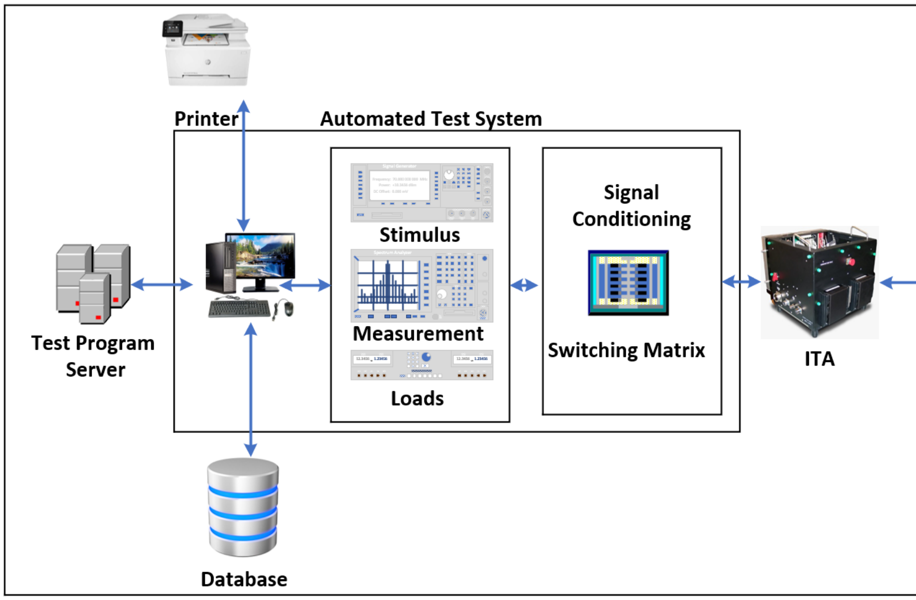

Fig. 2. A Simplified Automatic Test System Block Diagram

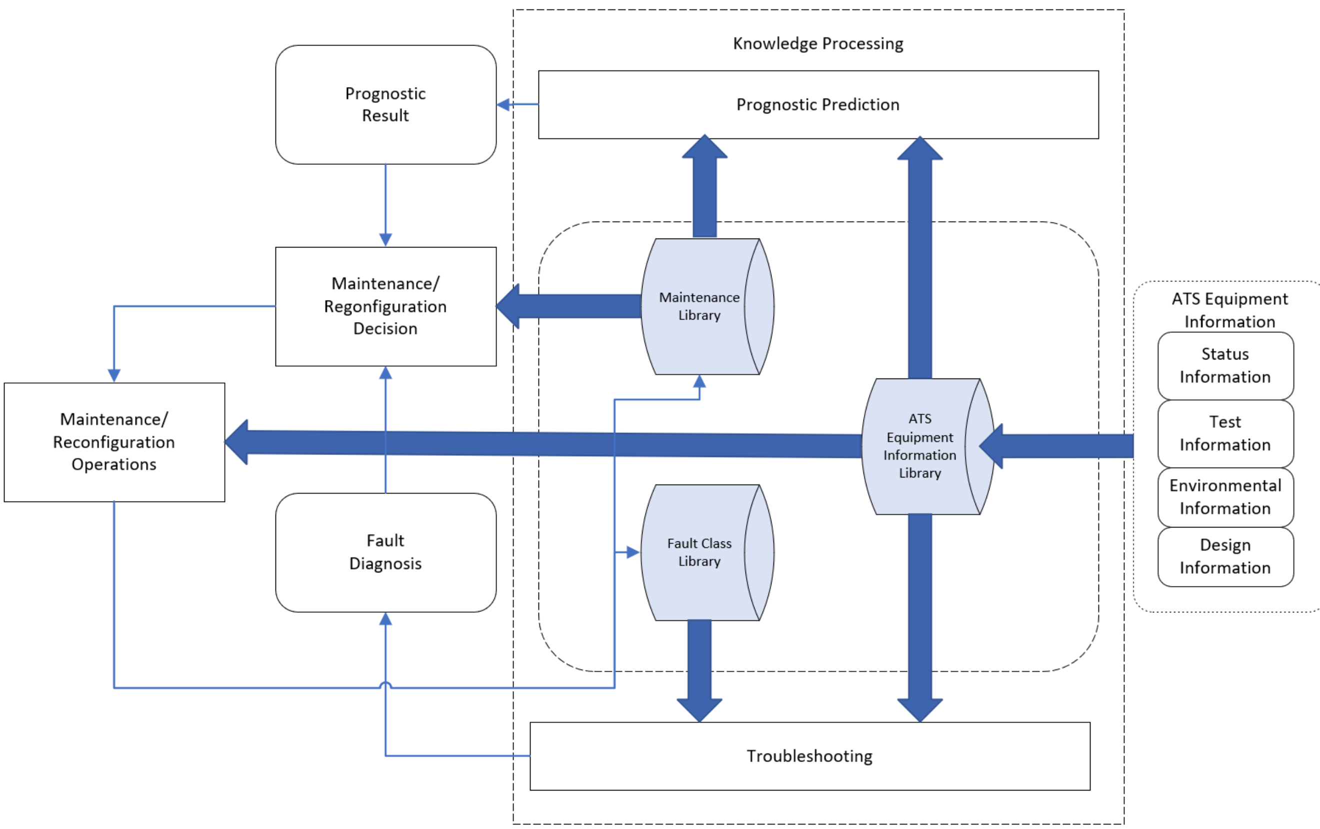

Fig. 3. An ATS Knowledge Model

the maintenance action can be planned with enough lead time to minimize the cost and operational impact of the occurrence of a failure. CBM differs from 'on-condition' maintenance in that under CBM, knowledge of asset condition at any given time provides an understanding of how much time is available before the required maintenance must be performed [5]." While not stated specifically in this definition, the goals of PHM are wholly consistent with CBM initiatives in focusing on proactive maintenance processes based on current health state.

Based on this definition, the SAE is also developing a new recommended practice that further describes CBM as "a maintenance practice based on monitoring the condition of equipment assets to determine whether they will fail *during some future period* [emphasis added], taking appropriate action to avoid the consequences of that failure. CBM employs real-time or approximate real-time assessments of data obtained from health-ready components or external tests and measurements using either portable equipment or actual inspection. The objective of CBM is to perform maintenance based on the evidence of need while ensuring safety, reliability, availability, and reduced life cycle cost [6]." This view employs the risk-based perspective described in Section II and allows for data to be collected in offboard settings as described in Section III. The ultimate goal is maximizing the availability of the system to provides its best ability to accomplish missions making use of that system.

V. Current Standards for ATS and PHM

As indicated in the standard's scope, the intent of the P2848 working group is to draw on existing standards that support ATS and PHM rather than define a whole new standard from the ground up. To that end, we draw inspiration from the IEEE 1856 [7], whose purpose is to define a framework for PHM of electronic systems. Here, we provide an overview of the key standards drawn upon in the definition of P2848. More detail on each of the standards can be found in [8] and in the standards themselves.

A. IEEE 1856

As mentioned, IEEE Std 1856 attempts to define a framework for PHM systems. Its focus is on basic definitions and provides some guidance for the evaluation of PHM systems. The scope of the standard states, "This standard covers all aspects of PHM of electronic systems, including definitions, approaches, algorithms, sensors and sensor selection, data collection, storage and analysis, anomaly detection, diagnosis, decision and response effectiveness, metrics, life cycle cost of implementation, return on investment, and documentation. This standard describes a normative framework for classifying PHM capability and for planning the development of PHM for an electronic system or product. The use of this standard is not required throughout the industry. This standard provides information to aid practitioners in the selection of PHM strategies and approaches to meet their needs [7]." Given the standard calls out the fact that the framework, as defined, is not required, the material contained serves more as recommendation, in spite of its normative language.

Of note are the performance measurements called out. These include 1) accuracy (a measurement of deviation from ground truth), 2) timeliness (a measure of the efficiency of the PHM system to make a recommendation), 3) confidence (a measure of trust or uncertainty in the recommendations made), and 4) effectiveness (a measure of how well mission goals can be achieved). The standard also allows for context-specific measures to be defined.

B. IEEE 1232

Proceeding from the understanding that prognostics is a generalization of diagnostics in that it assesses the evolution of health state in time, it was felt that diagnostic information was key to meeting the objectives of P2848. The most general standard on diagnostics is IEEE Std 1232. The scope of this standard states, "The AI-ESTATE standard defines formal specifications for supporting system diagnosis. These specifications support the exchange and processing of diagnostic information and the control of diagnostic processes. Diagnostic processes include, but are not limited to, testability analysis, diagnosability assessment, diagnostic reasoning, maintenance support, and diagnostic maturation [3]."

Of critical importance with the AI-ESTATE standard is the definition of different types of models and services to be used by a diagnostic reasoner, many of which can be incorporated into prognostic processes as well. These include models such as Bayesian networks [9] and D-matrices [10], both of which are widely used in diagnostics and prognostic tools. Work has also been done to extend the models to the prognostic domain, for example, through the use of dynamic Bayesian networks and Continuous Time Bayesian Networks [11], [12].

While P2848 is focused on data mappings, IEEE Std 1232 also provides definitions of software services. Many of these services can be employed in an ATS setting and in a PHM setting. The primary changes to be made would be with respect to data items returned by the services, especially as they relate to time-based inferences.

C. IEEE 1671

The IEEE 1671 Automatic Test markup Language (ATML) family of standards [1] are expected to play a prominent role in P2848. In particular, the P2848 standard will draw upon definitions of data items in the base IEEE 1671 standard [1], as well as IEEE 1671.1 (Test Description) [13], IEEE 1671.3 (UUT Description, focusing on Instance) [14], IEEE 1671.2 (Instrument Description, focusing on Instance) [15], and IEEE 1671.6 (Test Station Description, focusing on Instance) [16]. The scope of 1671 (and its family) is to define "a standard exchange medium for sharing information between components of ATSs. This information includes test data, resource data, diagnostic data, and historic data. The exchange medium is defined using XML."

The data types from the base standard are focused on defining properties of the capabilities and interfaces to ATS hardware and software elements. Both 1671.3 and 1671.6 provide definitions of classes and instances of UUTs and test stations respectively. This is significant for this standard since the focus is on PHM involving ATS, both as the means by which testing is done (test station) and as a UUT itself. We note that P2848 is expected to draw, as needed, from IEEE Std 1641, which focuses on signal and test definitions, insofar as it is needed to support the test station instance data items. The role of 1641 will not be covered further here.

D. IEEE 1636

Also of key importance to PHM-related activities is data collected through historical processes. Two key standards to be used fall within the IEEE Std 1636 SIMICA family of standards [2]. The scope of the standard is to provide "an implementation-independent specification for a software interface to information systems containing data pertinent to the diagnosis and maintenance of complex systems consisting of hardware, software, or any combination thereof. These interfaces support service definitions for creating application programming interfaces (API) for the access, exchange, and analysis of historical diagnostic and maintenance information." In terms of historical information, three areas provide focus: test results, maintenance actions, and diagnostic history. Note, however, that the diagnostic history information is covered by the *Diagnostic Context Model* defined by AI-ESTATE [3].

Test results information, as defined by IEEE Std 1636.1, focuses on "data resulting from executing tests of a unit under test (UUT) via a test program in an automatic test environment [17]." The intent is to capture the historical test information for a UUT as it is undergoing fault isolation or recertification testing. From the perspective of the ATS as UUT, test results are collected for self-testing, self-calibration, and calibration verification testing.

Whenever an action is taken on a UUT following testing, it is customary in the US Department of Defense to open a *maintenance action form* (MAF), which documents any maintenance actions taken. To assist in capturing this information in a standard way, IEEE Std 1636.2 was developed and approved "for exchanging maintenance action information (MAI) associated with the removal, repair, and replacement of system components to maintain/support an operational system [18]." The ultimate goal of the standard is to facilitation consistent capture of this maintenance information, from which *post hoc* analysis can be performed to improve diagnostic and maintenance processes. Such analyses would also support the PHM mission.

VI. Mapping ATML and SIMICA Data Elements

The IEEE P2848 Working Group has performed an in-depth analysis of the IEEE 1671 and IEEE 1636 families of standards, to identify existing XML data definitions that support the information exchanges necessary for implementing PHM on ATE. The analysis targets the following use cases:

1) Specify operation and performance of prognostics
2) Record prognostics results, in conjunction with test and diagnostics results, traced to individual prognostic subjects (UUT or ATE)
3) Reference prognostics results as reasons for maintenance actions
4) Support development of simulation models for prognostics
5) Support automatic generation of code for implementing test and prognostic procedures
6) Support automatic generation of documentation for prognostic procedures
7) Support determination of actual performance for implemented prognostics
8) Support life cycle of prognostic procedures (maturation, rehosting, etc.)

	Prognosis of the UUT, on ATE	**Prognosis of the ATE**
Inputs	Data generated by the execution of UUT test programs. Historical UUT maintenance information.	Data generated by the execution of ATE self-test and calibration programs and of UUT test programs. Historical ATE maintenance information.
Outputs	Failure predictions for: the UUT, UUT components, or UUT functions.	Failure predictions for: ATE instruments, ATE instrument components, or ATE instrument functions.

TABLE I
INTERFACE OF PROGNOSTIC PROCEDURE.

The results of the analysis are summarized in the diagram from Figure 4, which identifies the mapping of applicable ATML and SIMICA component standards to the data exchanges that support the target PHM use cases. The data items and data flows specific to these use cases, highlighted in red, are superimposed on a typical ATML- and SIMICA-based data flow for ATE-based test and diagnostics [1].

For the purpose of this analysis, we introduce the notion of a generic *prognostic procedure*, which takes as inputs data generated by the execution of test programs on ATE, as well as historical maintenance information, and generates failure predictions for the prognostic subject, its components, or its functions. The diagram showcases the similarities and differences, in terms of data flows, between diagnostic procedures and test procedures. The analysis focuses on the data interface of prognostic procedures (i.e., their inputs and outputs) and is agnostic relative to the prediction algorithms that implement specific prognostic procedures. Table I identifies these inputs and outputs, for the two scenarios addressed by the P2848 standard.

In the table, the "ATE instruments" category includes the switching subsystem, as well as ATE cables and connectors. The Interface Test Adapters used with UUTs are assimilated with the UUT, while the Interface Test Adapters used for ATE self-test and calibration are assimilated with the ATE.

The analysis concluded that many of the ATML and SIMICA component standards can be used unchanged for supporting PHM on ATE, for example:

- ATML UUT Description documents identify the UUT components or functions whose failure can be predicted. Similarly, ATML Test Station / Instrument Description documents identify the ATE instruments, ATE instrument components, or ATE instrument functions whose failure can be predicted.
- ATML UUT <u>Instance</u> documents identify individual UUTs that are subject to PHM. Similarly, ATML Test Station and ATML Instrument <u>Instance</u> documents identify individual test stations and instruments that are subject to

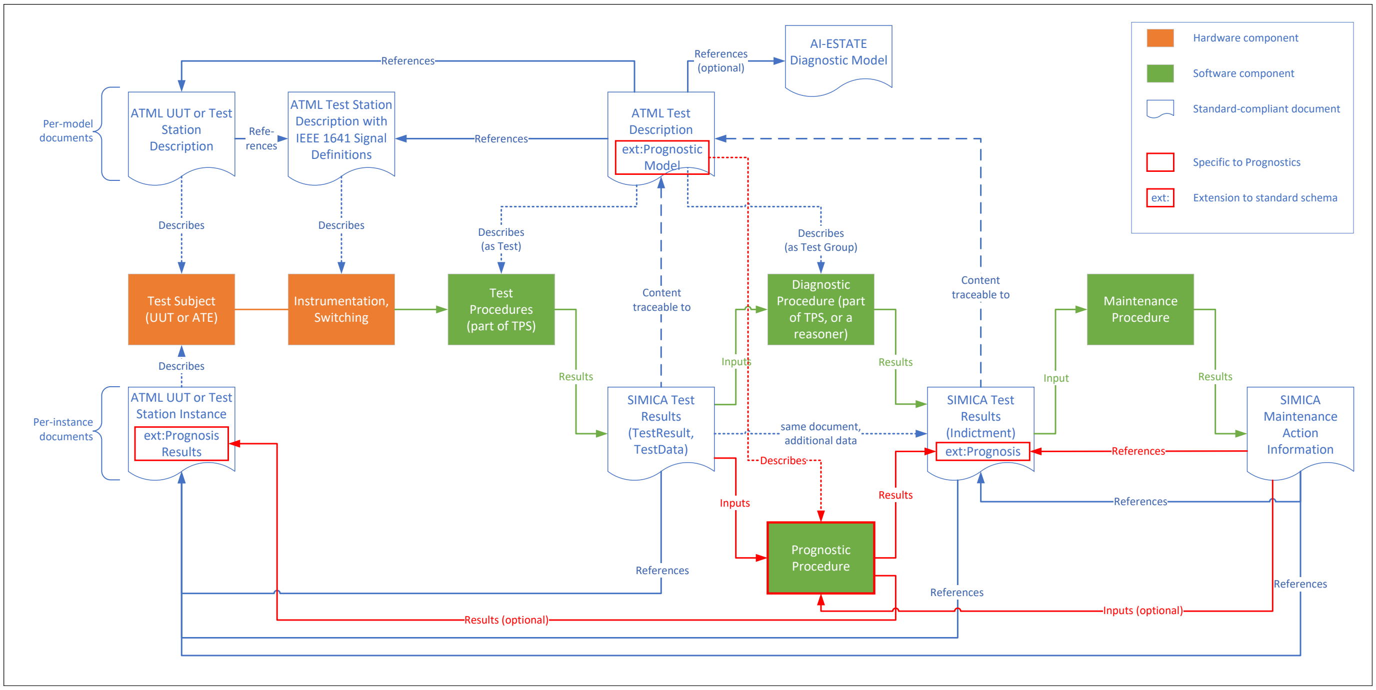

Fig. 4. Mapping of ATML and SIMICA Documents to the ATS-based PHM Data Flows

PHM.

- ATML Test Description describes the test procedures whose results are used by prognostic procedures
- SIMICA Test Results documents store test and measurement information used by prognostic procedures
- SIMICA Maintenance Action Information documents can store historical maintenance information for the UUTs or the ATE.

A few ATML components require extensions:

- ATML Test Description specifies the "TestGroup" type, which is used to describe diagnostic procedures(e.g., fault tree and fault dictionary). An extension is needed to describe prognostic procedures.
- SIMICA Test Results specifies the "TestResult" type, which is used to record Pass/Fail test results. An extension is needed to record prognostic results, which could include an estimated Remaining Useful Life (RUL) and a confidence level.
- ATML UUT Instance and ATML Instrument Instance store usage information for individual UUTs or instruments. They could be extended to store the estimated RUL.
- ATML Capabilities, specified in the root IEEE 1641 standard, allow the description of instrument characteristics such as range, resolution, and accuracy. To support PHM, these could be augmented with degradation information, for example: stability, reliability, expected degradation period or number of cycles (for relays).

Note that the extension mechanisms built into the ATML and SIMICA standards allow the definitions of PHM-specific XML types, which can be used in instance documents in combination with the existing types, without requiring changes to the existing standards or to their supporting XML schemas.

VII. ATML and SIMICA Extensions

The IEEE P2848 Working Group is in the process of defining the content and structure of extension types for PHM. For illustration, Figure 5 shows the draft UML diagram for a possible IEEE 1636.1 "TestResult" extension that can record prognostic results at three levels of fidelity:

1) Estimate that failure will occur (within a preset time), with confidence level
2) Estimate that failure will occur before a specified time, with confidence level
3) Estimated Remaining Useful Life, with confidence level

The use of an abstract base type provides an extension point, to accommodate additional prognostic result types, such as probability distributions produced by stochastic algorithms.

VIII. Conclusion

The IEEE P2848 standardization effort is a new initiative focused on providing a data-oriented foundation to support prognostics and health management in the context of automatic test systems.

The standard is still in the development stages with the most recent progress being focused on mapping data elements in existing ATS-oriented standards to the PHM pipeline. The reuse and extension of existing ATML and SIMICA standards aims to facilitate the integration of PHM with existing processes,

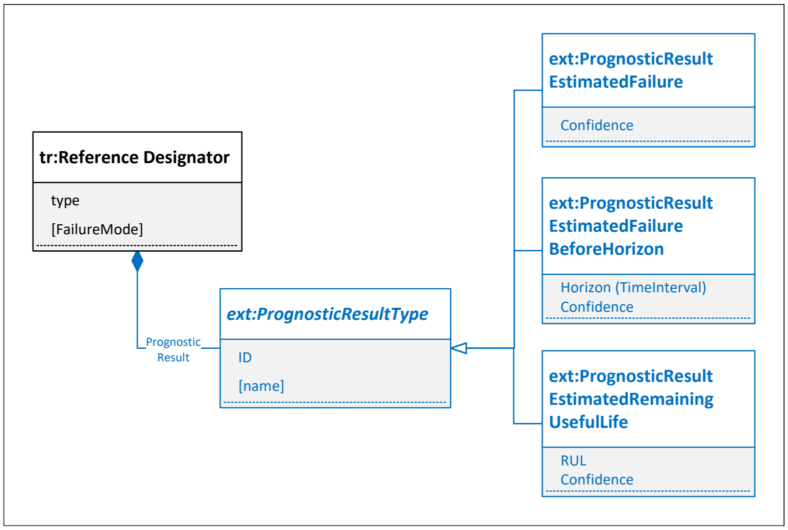

Fig. 5. Example: TestResult extension for prognostic results

software applications, and data stores that support ATS-based test and diagnostic.

Historically, PHM has focused on data captured during the operation of a unit or system, so this standard is unique in its focus on off-board test and maintenance information. Even so, the expectation is that this standard will provide a foundation for users of ATS (e.g., military, commercial aviation, rail, and automotive) to be able to introduce consistence, exchangeability, and interoperability of ATS assets in a way that provides additional opportunities for utilizing PHM. As different industries move towards implementing large-scale CBM+ processes, the goal is for this standard to fit into those processes seamlessly and provide added benefit in improving the life cycle support of such systems.

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Disclaimer

This paper does not reflect the opinions or positions of the IEEE nor of the P2848 Working Group itself. Rather, this paper is intended to provide an informal update of the workings of the P2848 working group from the perspective of some of its members.

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