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IEEE Standard Framework for Prognostics and Health Management of Electronic Systems

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IEEE Std 1856™-2017

IEEE Standard Framework for Prognostics and Health Management of Electronic Systems

Sponsor

Standards Committee
of the
IEEE Reliability Society

Approved 7 September 2017

IEEE-SA Standards Board

Abstract: Information for the implementation of prognostics and health management (PHM) for electronic systems is described in this standard. A normative framework for classifying PHM capability and for planning the development of PHM for an electronic system or product is also described in this standard. Manufacturers and end users can use this standard for planning the appropriate prognostics and health management techniques to implement and the associated life cycle operations for the system of interest.

Keywords: classification of electronics, electronic systems, health management, IEEE 1856™, implementation in electronics, PHM definitions, PHM functional model, PHM Metrics, PHM operational model, prognostics

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PDF: ISBN 978-1-5044-4319-7 STD22772
Print: ISBN 978-1-5044-4320-3 STDPD22772

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Introduction

This introduction is not part of IEEE Std 1856-2017, IEEE Standard Framework for Prognostics and Health Management of Electronic Systems.

Prognostics and health management is an approach to protect the integrity of equipment and avoid unanticipated operational problems leading to mission performance deficiencies, degradation, and adverse effects on mission safety. Researchers and application developers have developed a variety of approaches, methods, and tools that are useful for these purposes, but applications to real-world situations may be hindered by the lack of visibility into these tools, the lack of uniformity in the application of these tools, and the lack of consistency in their demonstrated results. There is a need for documented and favorable guidance that will encourage practitioners to invest the resources necessary to put these techniques into practice. While specific application domains often require customized treatment for PHM application development, some core principles apply to all. This document describes those core principles and exemplifies their application within the electronics domain.

While this standard presents the normative requirements for a PHM system, Annex A will act as a guide for those who wish to implement prognostics and health management for complex electronic components and systems. However, it is possible to extend the core principles described in this document to other application domains, such as systems comprising electro-mechanical, mechanical, and structural elements.

Contents

IEEE Standard Framework for Prognostics and Health Management of Electronic Systems

1. Overview

1.1 Background

The goal of this standard is to provide information for the implementation of prognostics and health management (PHM) for electronic systems. Within the system health management community, there are several different interpretations of the term *prognostics*, such as predictive analysis, reliability prediction, damage accumulation prediction, or condition-based prediction. This standard can be used by manufacturers and end users for planning the appropriate prognostics and health management methodology to implement and the associated life cycle operations for the system of interest. This standard aims to provide practitioners with information that will help them make business cases for PHM implementation and select proper strategies and performance metrics to evaluate PHM results. The overall aim is to provide a broad overview of PHM while at the same time provide significant details to assist the practitioner in making appropriate decisions.

1.2 Scope

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[1]. This standard provides information to aid practitioners in the selection of PHM strategies and approaches to meet their needs.

1.3 Purpose

The purpose of this standard is to classify and define the concepts involved in PHM of electronic systems and to provide a standard framework that assists practitioners in the development of business cases and the selection of approaches, methodologies, algorithms, condition monitoring equipment, procedures, and strategies for implementing PHM of electronic systems.

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[1]At the time of adoption of this standard, there is no known external requirement to use a PHM standard. There is no external agency or regulatory body that is promoting the application of this standard. It is expected that after the approval of this standard, the industry will start using this standard to generate the requirements of PHM systems that will be included in their particular system or products/ applications.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std 15288, Systems and software engineering—System life cycle processes.[2,3]

IEEE Std 12207, Systems and software engineering—Software life cycle processes.

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[4]

data management: The function of controlling the acquisition, analysis, storage, retrieval, and distribution of data.

decision time: The measure of how quickly a response decision is made, given a set of diagnostic and prognostic inputs.

detection accuracy: A quantification of the number of correctly detected failure cases, often expressed as a ratio of correctly classified cases to the total number of scenarios.

detection time: The measure of how quickly an off-nominal condition is detected and measured from the time the physical behavior being monitored exhibits failed, degraded, or anomalous behavior.

diagnostic time: The measure of how quickly a fault is isolated and (if required) identified, given a set of failure and anomaly detection inputs.

diagnostics: The action of determining the cause of an error in location and nature.

NOTE—This is a fault discovery approach that involves two steps: fault isolation and fault identification. First, the location of the fault is determined (fault isolation). Then, the type of fault is identified (fault identification).[5]

end-of-life: The moment in time when a component or a system does not perform its intended function within desired specifications (Saxena, et al., 2008 [B15]).

NOTE—End-of-life is equivalent to end-of-useful-life.

health: Summary information regarding the current ability of a system or subsystem to perform its intended function.

NOTE—A product's health state is not always directly observed and hence it is estimated.

health management: The process of decision-making and implementation of actions based on the estimate of the state of health derived from health monitoring and expected future use of the system.

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[4]*IEEE Standards Dictionary Online* is available at: http://dictionary.ieee.org.
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NOTE—Health management includes the decision of what response actions to take and the actions themselves, which may include operation, repair, replace, re-allocate resources, re-prioritize function/change system goals, and remove/shutdown. These actions may be taken individually or in some combination based on the health and future mission information available.

health monitoring: The function of estimating a system's health state, including measurement of state variables and identifying if the states of these variables indicate an off-nominal condition.

isolation accuracy: A quantification of the accuracy in classifying the fault to belong to a particular component type or failure mode.

object system: The system (or a sub-system) that is the subject of the prognostics and health management activity.

prognostic distance: The time interval between the first time instance at which a prediction meets desired performance (accuracy, precision, and/or confidence) and the estimated failure time of the system (Saxena, et al., 2008 [B15]).

prognostic system accuracy: A quantitative measure of the error between the predicted end-of-life and the observed end-of-life of the monitored component/system.

prognostic time: The measure of how early, before an actual failure event, a prognostic system produces an accurate (as defined in an accuracy metric) prediction of end-of-life.

prognostics: The process of predicting an object system's RUL by predicting the progression of a fault given the current degree of degradation, the load history, and the anticipated future operational and environmental conditions to estimate the time at which the object system will no longer perform its intended function within the desired specifications.

remaining useful life (RUL): The length of time from the present time to the estimated time at which the system (or product) is expected to no longer perform its intended function within desired specifications.

response time: A measure of how quickly a response is executed, from the time the response is initiated until response completion.

4. Requirements

The following shall be applicable with regard to prognostics and health management for electronic systems:

a) A prognostics and health management system shall consist of sub-systems and components with capabilities including:

   1) Acquisition of object system data (e.g., by means of sensors),

   2) Data management, and

   3) Data processing algorithms and/or processes for:

      i) Diagnostics, health state estimation, and prognostics

      ii) Health management

b) The PHM system shall be developed in accordance with IEEE Std 15288[6] or an equivalent standard as defined in the PHM or object system specifications.

[6]Information on references can be found in Clause 2.

c) The PHM software and/or firmware shall be developed in accordance with IEEE Std 12207 or equivalent standard as defined in the PHM or object system specifications.

d) PHM system performance is measured for its contribution to achieving or improving object system goals. PHM system performance shall be measured in terms of metrics chosen from the following categories:

   1) *Accuracy:* Accuracy is a measure of deviation of a prognostic or diagnostic output of current object system state from measured, observed, or inferred ground truth. Accuracy shall be measured by comparing prognostic and diagnostic outputs from measured ground truth using several metrics (Saxena, et al., 2010 [B14][7]) such as, but not limited to, detection accuracy, isolation accuracy, and prognostic system accuracy. These terms are defined in the normative definitions section above.

   2) *Timeliness:* Timeliness is a measure of how quickly the PHM system's functions produce their outputs in relation to the failure effects that they are mitigating. Overall timeliness includes the total time of state estimation and control for the PHM Control Loop. The timeliness from prediction or detection through response shall be summed up to compare to the time required for the failure mitigation. If desired, comparisons for the prognostics function and the health management function shall be made separately by grouping the relevant sub-functions. The timeliness aspects of the PHM sub-functions that contribute to the total PHM Loop include detection time, diagnostic time, prognostic time, decision time, and response time. These terms are defined in the normative definitions section above.

   3) *Confidence:* Confidence is a measure of trust (or, conversely, a measure of uncertainty) in a PHM system's output. For detection and diagnostic functions, it is computed through, but not limited to, robustness, sensitivity, and uncertainty metrics. For prognostics it is specified by including the estimation of uncertainty in predictions and stability of predictions over time, in addition to sensitivity and robustness measures (Saxena, et al., 2010 [B14]).

   4) *Effectiveness:* Effectiveness is a measure of the PHM system's ability to preserve or attain relevant system goals. Typical effectiveness goals include system reliability, safety, performance, cost, or schedule. The sub-metrics of accuracy, timeliness, and confidence shall be combined for specific PHM mechanisms and for the PHM as a whole for the system to generate the PHM effectiveness measured against the relevant system goals, as allocated to PHM.

   5) And, any additional metrics as defined in the PHM or object system specifications.

e) PHM system performance shall be tracked over time to determine if a need exists to either update the PHM system (e.g., models, instrumentation, algorithms, rules, etc.) or performance measurement methods and metrics. The tracking system shall be capable of documenting all anomalies and failures during testing and operation, including tests and analyses to confirm them. The tracking system shall also document the outcomes and reports of the resulting investigations, design and operational modifications, and the results of tests of these modifications. Finally, the tracking system shall be capable of generating metrics regarding all of the above.

NOTE—The illustrations and notes presented in this Clause are provided to help the reader to understand the concepts and are not a requirement of the standard.

Figure 1 presents the times related to health monitoring and prediction events in the operational life of an object system. First of all, the designer specifies the upper and lower failure thresholds, and the upper and lower off-nominal thresholds for the PHM sensor in the system. Here, t_0 can be assumed to start at any time, e.g., when the system is turned on, and t_E is the occurrence of the off-nominal event. Off-nominal events occur when the PHM sensor measures an exceedance of the threshold limits specified by the PHM designer. The PHM metrics are initiated when such an event is detected at time (t_D) by a PHM system. The PHM system

[7]The numbers in brackets correspond to those of the bibliography in Annex B.

then computes a predicted failure time of the part or subsystem with its associated confidence interval. The response time (t_R) is the amount of time the PHM system uses to produce a predicted time of failure and make a usable prediction at time t_P. All these data can be stored in the memory and left to the designer to develop specific algorithms that employ them for managing their specific systems.

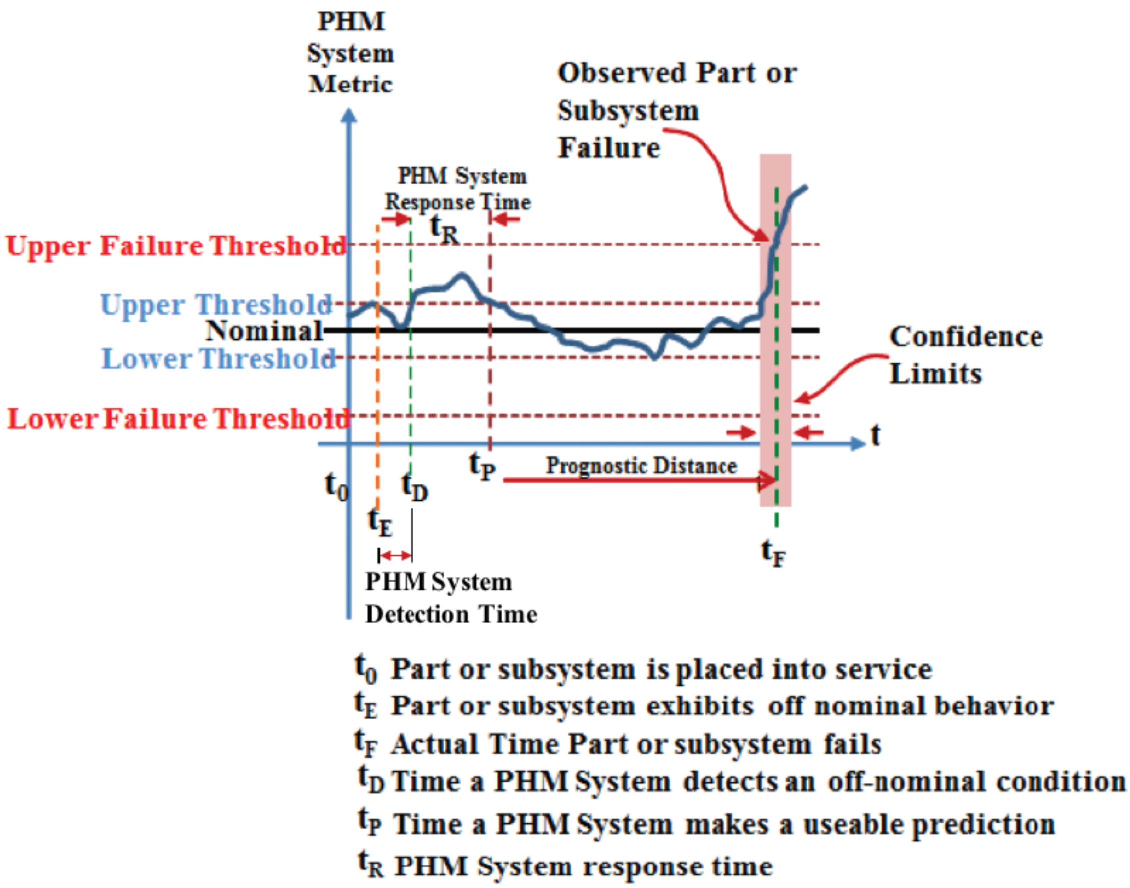


Figure 1—Milestones on the path to object system failure

Figure 2 helps to describe the relationships among some of the PHM metrics. Figure 3 presents an example of comparison between two prognostic algorithms based on a particular metric.

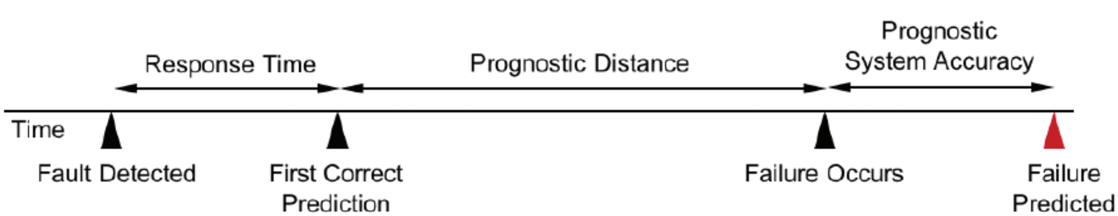
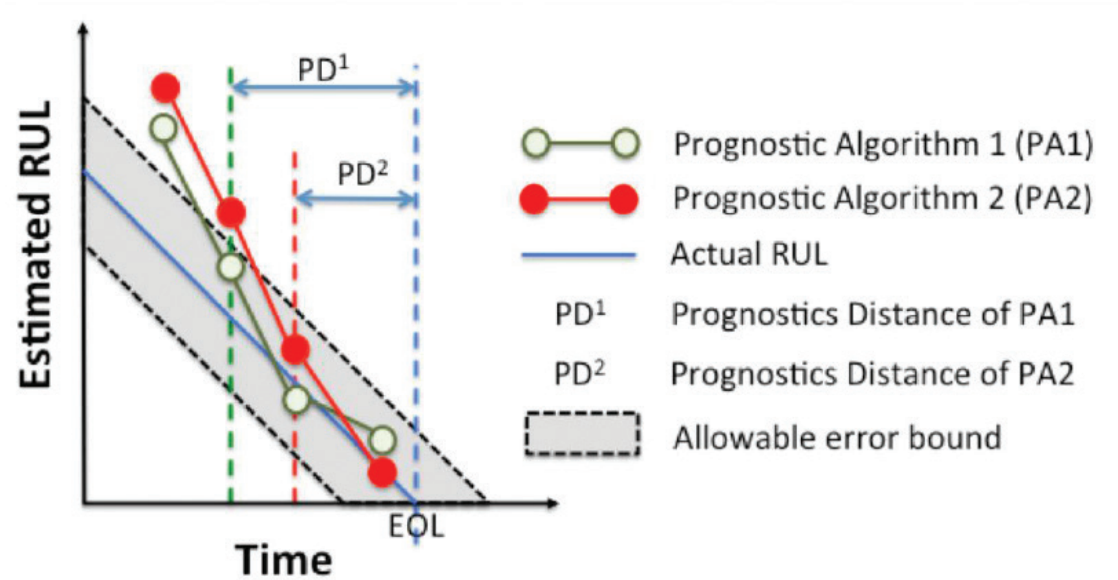


Figure 2—Relationship between metrics (Saxena, et al., 2014 [B16])



NOTE—Prognostics distance is an offline metric that is used to evaluate a prognostic algorithm using offline collected data.

Figure 3—Illustration of prognostics distance while comparing two prognostic algorithms based on point estimates of the Remaining Useful Life (Saxena, et al., 2010 [B14])

Annex A

(informative)

Guidance for PHM System Implementation

A.1 Preliminary considerations

A.1.1 Return on investment on PHM

When designing any engineering system in general, and a PHM system in particular, it is important to consider the costs and benefits of the system. This section is to serve as a discussion of the considerations that are encouraged be addressed prior to the implementation of the PHM system. As the end user refers to this standard to design a PHM system, it is encouraged that they be aware of the costs that are incurred in the design, in addition to the benefits that a PHM system provides.

Return on investment (ROI) may be defined as the ratio of gain to investment. A major consideration before implementing PHM for any system is the determination of whether it provides value (safety, cost, availability, etc.) that is greater than the expense of developing and incorporating it in the first place. The classical definition of return on investment focuses on the financial consideration of the amount of future money saved (i.e., future spend avoided) by implementing the system versus the amount of money spent to develop and implement the system.

Implementation costs are the costs associated with designing, implementing, and maintaining the prognostics and health management system. More broadly, the implementation costs may be broken down into three categories: recurring, non-recurring, and infrastructural costs (Feldman, et al., 2009 [B4]). Recurring costs are accumulated throughout the product life cycle and may be associated with replacing sensors, adding components, etc. Alternatively, the non-recurring costs are associated with a singular event, such as initial design and material costs. Infrastructure costs are associated with the initial investment plus yearly infrastructure upgrades. Some examples of these costs are provided in Table A.1.

Table A.1—Potential implementation costs for a PHM system

Recurring	Non-recurring	Infrastructural
Maintenance of a PHM system (sensor replacement/repair) Potential for unused remaining useful life Testing for calibration /verification	Sensors Data collection	Data storage

Cost avoidance is a byproduct of the successful implementation of a prognostics and health management system. This cost avoidance may manifest itself as either real-time failure avoidance or an advance notice of incipient failure. Real-time failure avoidance can be measured as a savings of costs that would have been incurred in the future because it prevents costly system failure, mission failure, and possibly injury or loss of life. While money is a crucial factor, it is important to realize that the potential benefits of an effective PHM system include the following:

— Increased safety
— Increased availability
— Improved reliability
— Reduced spares

These benefits may not be reflected in a strictly cost-based ROI calculation (Feldman, et al., 2009 [B4]). Furthermore, there are benefits that may not be immediately recognized within the confines of the PHM system, including the data generated from systems and components that are used and monitored in the field. These data can be used to improve future designs.

A.1.2 PHM metrics

Prognostic metrics are used to measure the effectiveness of the chosen PHM scheme. The metrics used to evaluate prognostics is a direct function of the field of application. There are several different classes of metrics used for prognostics, diagnostics, and health management. The metrics can be based on algorithm performance (accuracy, sensitivity, robustness, etc.), computational complexity, and cost–benefits metrics (Saxena, et al., 2008[B15]).

PHM system performance metrics need to be changed to accommodate the following scenarios:

— As a system ages, the initially implemented PHM design (system and PHM models) may become obsolete and, therefore, require an update or tuning of parameters such that the original performance criteria specified in the requirements can continue to be satisfactorily met.

— As a system ages, it may require changes (design refreshes) in order to remain supportable. The PHM structures (hardware and software) may have to be refreshed to remain effective. It is also possible that the PHM structures themselves will become unsupportable due to obsolescence and have to be refreshed.

— With time and changing operational contexts, the PHM requirements for a system may evolve and/or change, and, therefore, provisions to change the PHM system, including new PHM hardware, models, and/or metrics, and updated performance specifications for the original metrics should be available.

A.1.2.1 Example

Fault Management (FM) metrics have been applied successfully to the National Aeronautics and Space Administration's (NASA) Space Launch System (SLS) program. One of SLS's primary goals is to ensure the safety of the crew during its operation to take the Orion crew capsule from Earth's surface into space. To assess this, SLS uses a Loss of Crew (LOC) metric, which in turn is based on a series of calculations that includes FM metrics for the effectiveness of aborts to return the crew back to Earth in case of failure of the SLS. These calculations are summarized in Y. Lo, et al. [B7].

For SLS, the FM metrics calculations are always performed on a "per failure scenario" basis, and then are probabilistically summed to estimate the total system-wide metric. In the SLS case, the LOC metric for each failure scenario is calculated as (1-abort effectiveness) per failure scenario that can cause a Loss of Mission (LOM) scenario, from which an abort is needed. The total LOC metric then sums the probability-weighted LOC metric for all failure scenarios. Within each LOM scenario, the abort effectiveness calculation is calculated as a set of contingent probabilities that the series elements of the Fault Management Control Loops (FMCL) involved in each LOM scenario are effective. Thus, the total FMCL calculation consists of the product of the following probabilities:

— The probability that a failure is potentially detectable (covered)

— The probability that the failure is actually detected

— The probability that the failure is isolated to determine its location

— The probability that the correct failure response action is determined and selected

— The probability that the failure response action is successful. For SLS, this means that the abort response action successfully enables the crew to escape the immediate SLS hazard (such as explosion or loss of control) and brings the crew safely back to Earth.

If at any step, there is a probability that the function (coverage, detection, isolation, response determination, and response action) fails, then the FMCL fails and that probability is added to the absolute LOC value for that scenario. Conversely, the probability that the entire set of FM functions succeed yields the abort effectiveness value for that FMCL in that scenario. Given that there can be more than one possible FMCL that activates (two different detections with two different timings might activate, yielding two different probabilities of successful abort), then a weighted average of the two FMCLs is taken to yield the overall abort effectiveness per LOM scenario. As noted above, the abort effectiveness of all scenarios is probabilistically summed to yield the total abort effectiveness for all of the Fault Management for the system.

A.2 The PHM system view

A.2.1 Background

The term "Prognostics and Health Management," as used in this document, is meant to encompass both the monitoring and data processing functions inherent within the electronic component, board, subsystem, and system, used to (proactively) manage and restore the system's health. These functional elements are required in order to deliver a "health-ready" (i.e., PHM-ready) electronic component or system to enable the PHM capability.

A.2.2 PHM functional reference model

A PHM system consists of the core capabilities summarized in Figure A.1. As shown in the diagram, the core PHM operational processes (Sense, Acquire, Analyze, Advise, and Act) are enabled by the PHM functions included in the electronic system. As described in the diagram, the core electronic system PHM functions include functional elements for Sensing (S), data acquisition (DA), data manipulation (DM), state detection (SD), health assessment (HA), prognostic assessment (PA), advisory generation (AG), and health management (HM).

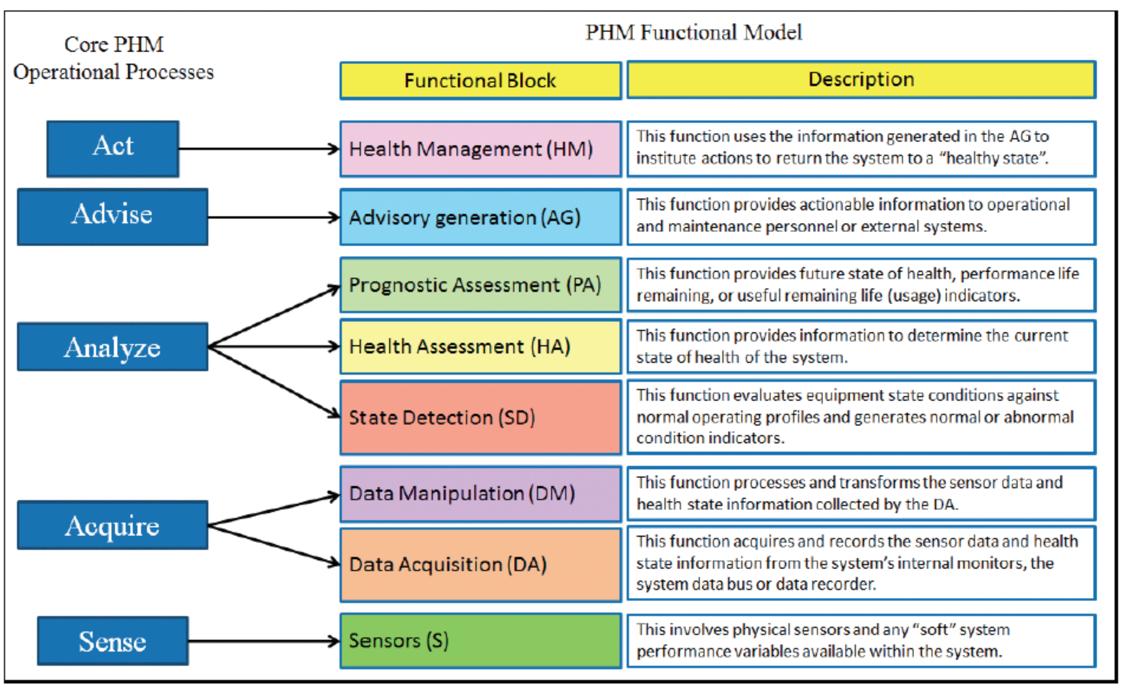


Figure A.1—PHM functional reference model

In this model, the lower three functional blocks provide low-level, application-specific functions. At the lowest level, a sensor(s) produces an output state that corresponds to a state in the object system or the object system's environment. At the next level, the Data Acquisition block converts sensor output to digital data. The next level, the Data Manipulation block, implements low-level signal processing of raw measurements from the DA block. The State Detection function supports modeling of normal operation and the detection of operational abnormalities.

The upper three functional blocks of the model provide decision support to operations and maintenance personnel based on the health of the target system. Within this group, the Health Assessment function provides fault diagnostics and health condition assessment. The Prognostics Assessment function forecasts the health condition based on a model, current data, and projected usage loads and computes performance remaining useful life. The Advisory Generation function provides actionable information related to the health of the target system. Finally, the Health Management function converts the information from the advisory generation function into actions that will manage the health of the system to achieve overall system and mission objectives. The various models used in the PHM system functions are subject to review and discussion in the design and assessment process.

A.3 PHM system operational view

Figure A.2 provides a general operational view of how the sensors, health monitoring, and assessment functions inherent within the electronic system enable the PHM capability operational processes.

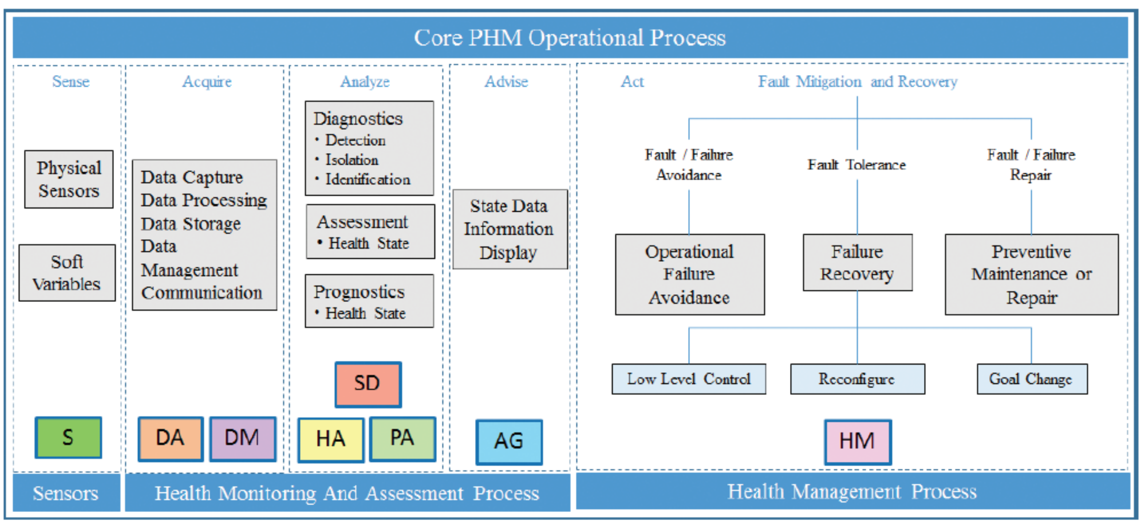


Figure A.2—PHM system operational view

As shown in the diagram, the Sense process is enabled by the data from the system's physical sensors and any "soft" system performance variables available within the electronic system.

The Acquire process is enabled by the data acquisition and data manipulation functions inherent in the system design. This includes data capture, processing, storage, data management, and data communication.

The Analyze process is enabled by the state detection, health assessment, and prognostic assessment functions inherent in the system design or external to the system. This includes fault detection, isolation and identification, assessment of the system's health state, and estimation of the performance life remaining.

The Advise process is enabled by the advisory generation (AG) function inherent in the system design or external to the system. This includes presentation of health state data, prescriptive information, or display advisories.

Finally, the Health Management processes uses the information generated in the Advise section to institute actions to return the system to a "healthy state." The fault mitigation and recovery processes shown in the diagram may be performed within or external to the system. The idea here is to provide both a level of autonomous failure tolerance and recovery as well as operator-initiated failure avoidance and preventive maintenance actions. Together, these system design functions and processes comprise the enterprise PHM capability.

A.4 Informative definitions

Terms relevant to PHM are listed and defined in this section. The definitions as provided here apply specifically to the application of this standard. When applicable, the specific references that relate to definitions found in the *IEEE Standards Dictionary Online*, or in other IEEE documents are noted.

anomaly: Any deviation from required, expected, or desired performance of the object system.

NOTE—Please refer to the definition of anomaly in *IEEE Standards Dictionary Online* [(C/SE) 1074–1995s].

behavior: The temporal evolution of a state.

canary device: A canary device is a component that provides early warning of impending failure.

NOTE 1—The canary device should experience the same environmental and operational loading conditions as the system that it is monitoring (Dasgupta, et al. [B3]).

NOTE 2—The canary device should not influence the operation of the monitored system.

NOTE 3—While it is preferred that the canary device should fail by the same failure mechanism as the monitored system, it may fail by a different failure mechanism as long as there exists a clear and quantitative mapping between the canary device's failure mechanism and the object system's failure mechanism (Mathew [B8]).

condition-based maintenance: Condition-based maintenance (CBM) is a proactive repair activity based upon the health status of a system at any particular time.

corrective maintenance: Repair activity that is undertaken to rectify degradation or failure so that the system can be restored to its normal operable state.

cost avoidance: A reduction in costs that have to be paid in the future to sustain a system.

NOTE—Cost avoidance is used rather than cost savings in sustainment planning because savings implies that there is money to give back, which there is not.

cost of ownership: Total cost of owning a product, system, or service.

NOTE—Cost of ownership is similar to life-cycle cost, but it is broader in scope. Cost of ownership includes the life-cycle costs, which are passed along to the owner or user through the product, system, or service price, plus the infrastructure and business process costs borne by the owner or user (Sandborn, 2013 [B12]). These additional costs may include: insurance, liability, installation, costs of operation, costs of out-of-warranty maintenance, and accounts for the remaining (residual or salvage) value at the end of ownership or useful life.

data fusion: Data fusion refers to the acquisition, processing, and synergistic combination of information gathered from multiple sources, possibly dissimilar in terms of location or sensor type.

degradation: Degradation refers to the cumulative effects of stress or aging in equipment or materials that results in the decreased performance of intended function.

NOTE—Degradation is generally considered irreversible in the absence of maintenance intervention. Examples of degradation include: corrosion, corrosion fatigue, creep, cycling fatigue, fouling, fractures, hydrogen embrittlement, oxidation, stress corrosion cracking, wear, and yielding.

failure: The unacceptable performance of intended function.

NOTE—Failure results from deviations in characteristic(s) beyond specified limits such as to cause an unacceptable reduction in the required function. The limits referred to in this category are special limits specified for this purpose. Please refer to the definition of failure in the *IEEE Standards Dictionary Online*.

failure detection: The process of deciding that a failure exists.

failure mechanism: The physical, chemical, electrical, mechanical, or other process(es) that results in a failure [B6].

failure mode: The effect by which a failure is observed to occur (IEEE Std 1413.1-2002 [B6]).

failure precursor: A failure precursor is any change in system parameter(s) that precedes the onset of failure.

failure recovery: An action taken to restore functions necessary to achieve existing or redefined system goals after a failure.

failure response: An action taken to attempt to retain or regain the system's ability to control the system state in reaction to a failure.

failure response determination: Identifying actions to mitigate a current or future failure.

failure site: A failure site is the physical location within the system where the failure has manifested.

failure threshold: Failure threshold is the acceptable limit(s) beyond which changes in the measured values indicate a function performance has become unacceptable.

false negative: An incorrect decision that a condition does not exist when it actually does exist.

false positive: An incorrect decision that a condition exists when it actually does not exist. Synonymous with the term false alarm.

fault: A physical or logical cause internal to the system that explains a failure.

NOTE—A fault is an anomalous condition that can cause an object system failure. There is often a time gap between the emergence of a fault and the failure.

fault containment: Preventing a fault from causing further faults.

fault identification: The process of determining the possible cause(s), severity, and temporal extent (temporary or permanent or intermittent) of a fault.

fault isolation: Determining the locations of hypothesized fault(s) to a defined level of granularity.

fault tolerance: This refers to the ability of the system to perform its intended functions in the presence of independent faults without causing system failure.

function: The transformation of an input state to an intended output state. (Alternatively: A passive or active transformation of inputs into outputs to achieve an intended purpose.)

goal/objective: The purpose of one or more intended functions or an intended purpose for which a system or part of a system is designed to achieve.

NOTE—A formal way of defining a goal is as the constrained outputs of a function. If a function is defined as $y(t) = f(x,t)$ with output states y and input states x both dependent on time, t, then goal G is defined as being achieved when $R_{lo}(t) < y(t) < R_{hi}(t)$, where $R_{lo}(t)$ and $R_{hi}(t)$ are the intended ranges, limits, or constraints on $y(t)$, which in turn is the output state vector of $f(x,t)$.

life cycle: A system's life cycle refers to the distinct stages that the system goes through from its conception to disposal.

NOTE—The stages may include all or a subset of the following: conception, definition/requirements capture, specification, design, prototyping or testing (including qualification and certification if applicable), production (or implementation), operation and support (O&S) or operation and maintenance (O&M), possible upgrade or modification, retirement, and disposal (if applicable). All life-cycle stages require unique resources and have unique costs.

life cycle cost: Life-cycle cost (also referred to as LCC or through-life cost) is the sum of all recurring and non-recurring costs over the complete life of a system or service (Sandborn, 2013 [B12]).

NOTE—Life-cycle costs include: design, documentation, manufacturing, installation, training, operating, maintenance (including misdiagnosis, business interrupt, and warranty resolution), upgrade, financial, and disposal. Life-cycle costs may be borne by any entity or a combination of entities, including the designer, manufacturer, and customer.

logistics: Logistics is the management of the flow of goods, information, and other resources, including energy and people, between the point of origin and the point of consumption in order to meet the requirements of the customer (Blanchard [B2]).

NOTE—The basic functions that logistics comprises include: material flow, distribution, and the life-cycle maintenance and support of a system throughout its intended period of use. In the case of electronic systems, logistics may include the acquisition, storage, relocation, and management of spare parts and other resources necessary to manufacture or support a system.

overstress failure: Overstress failure arises as a result of a single load (stress) condition that exceeds the material strength (IEEE Std 1413 [B6].

performance-based logistics: Performance-based logistics (also referred to as PBL, or performance-based life-cycle product support) refers to a group of strategies (and contractual mechanisms) for system support wherein, instead of contracting for goods and services, a contractor delivers performance outcomes as defined by performance metric(s) for a system.

NOTE—PBL is a subset of outcome-based contracting through which the customer pays for the delivered outcome instead of paying for specific logistics activities, system reliability management, or other support tasks. PBL contracts are normally executed at three levels: component-level, subsystem-level, and system- or platform-level.

physics of failure: Physics of failure (PoF) is an approach to understanding failure modes and mechanisms based on the response of the material properties and geometry of a component to the life cycle loading conditions (Pecht and Dasgupta [B11]) within an object system.

preventive maintenance: Preventive maintenance is the policy for care and servicing of a non-failed system for the purpose of maintaining it in satisfactory operating condition before a failure results in downtime.

NOTE—Preventive maintenance may take the form of systematic inspection, detection, and correction of incipient failures either before they occur or before they develop into major defects. Fixed-interval maintenance is a form of preventive maintenance.

reliability: The probability that an object system will perform its intended function for a specified interval under stated conditions.

NOTE—PHM requirements may have an objective to preserve or extend the object system's operational reliability. PHM is an enabler for improved mission/service reliability.

resilience: Robustness to internal and external uncertainties and disturbances that affect a system's ability to achieve its goals.

return on investment: Return on investment (ROI) is the monetary benefit derived from having spent money on developing, changing, or managing a system (Feldman, et al., [B4]).

NOTE—ROI is a common performance measure used to evaluate the efficiency of an investment or to compare the efficiency of a number of different investment options.

root cause: The root cause is the most basic causal factor or factors that, if corrected or removed, will prevent the recurrence of an event (ABS Group [B1]).

scheduled maintenance: Scheduled maintenance refers to maintenance activities (inspection and/or servicing) that take place on a regularly scheduled basis measured in calendar time, mileage, operational hours, or other relevant usage metric. Generally, scheduled maintenance activities take place at times (and locations) chosen by the system supporter.

sensor: A device that produces an output state that corresponds to a state in the object system or the object system's environment.

state: The value of a set of physical or logical variables.

sustainment: Sustainment refers to all activities necessary to: a) keep an existing system operational so that it can successfully complete its intended purpose; b) continue to manufacture and install versions of the system that satisfy the original requirements; and c) manufacture and install revised versions of the system that satisfy evolving requirements (Sandborn, 2008 [B13]).

time to criticality: The minimum time from the onset of a failure mode to when a critical system goal is compromised.

true negative: A correct decision that a condition does not exist.

true positive: A correct decision that a condition does exist.

unscheduled maintenance: Unscheduled maintenance refers to unpredicted or unpredictable maintenance requirements that were not previously scheduled, but require prompt attention and must be added to, integrated with, or substituted for previously scheduled workloads.

A.5 Levels of PHM implementation in electronics

A.5.1 Background

An electronic object system needs to be classified properly so as to help the manufacturer or user decide on the appropriate methodology for implementing PHM capabilities. Here, the classification is presented in the form of PHM implementation levels based on the size, function, and complexity of the object system under consideration. Each unique level has various failure modes and mechanisms that lead to various preferred schemes for PHM. The overall decisions regarding where PHM functions are placed within the object system remain a business choice, namely performance and cost-minimization. However, knowing the critical failure modes and mechanisms, and the required functions at each level, allows the design engineer to:

- Select appropriate PHM sensors for the failure phenomenology that underlies the critical failure,
- Develop and design efficient interfaces from the part/unit/subsystem to the PHM system,
- Collect PHM data with the necessary resolution and frequency for the part/unit/subsystem being monitored to enable PHM predictions, and
- Hierarchically construct the PHM capabilities from the various host system levels (part/unit/subsystem) to enable the employment of PHM data fusion and predictive host system prognostics.

Assuming that this classification is done by the product manufacturer, the levels of PHM implementation are illustrated in Figure A.3. As shown in the diagram, the idea is to integrate each level of PHM functionality by linking the health state data required by the next higher level to enable the full PHM capability. This is best accomplished by using the common "PHM Functional Model" (S, DA, DM, SD, HA, PA, AG, HM) as the reference or framework to perform engineering design analysis at the device, component, assembly, system or system of systems level in order to characterize existing foundational layers, design the integration strategy and identify necessary, and potentially missing, functions required to implement PHM. Together, these functional elements work to achieve the health management and prognostics capabilities required for the object system.

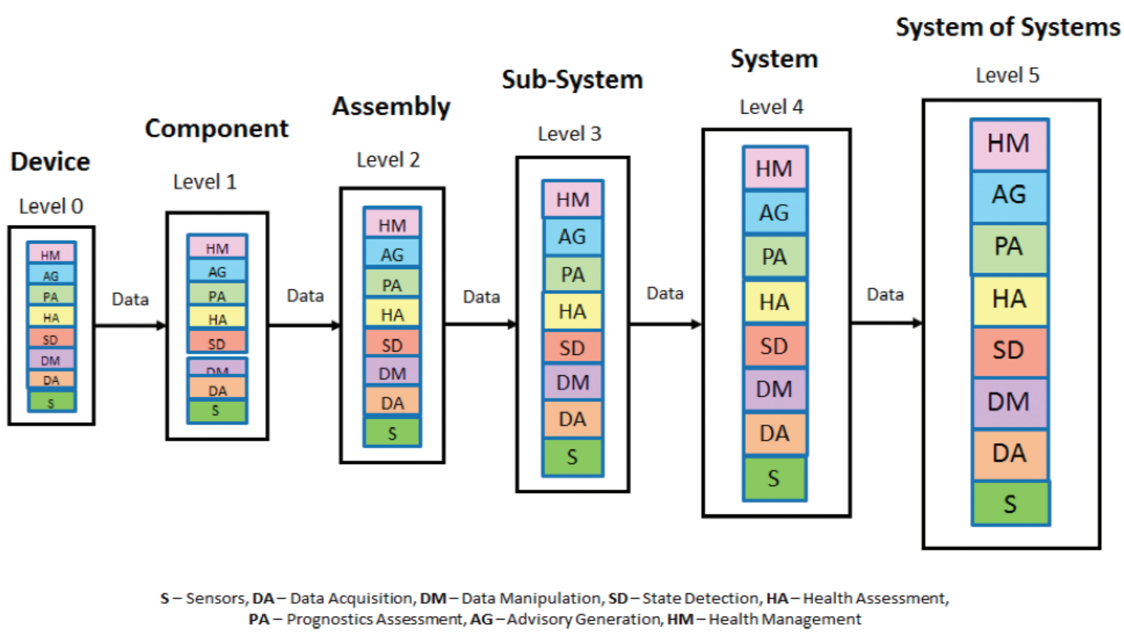


Figure A.3—PHM functional model implementation across levels of electronics

A.5.2 Device level

The device level represents the lowest level of complexity that makes up an overall system. For electronics applications, the device level would include the chip and on-chip sites, including the circuits, die, and metallization (Gu, et al., [B5]). The device level is referred to as Level 0.

A.5.3 Component level

The component level represents the lowest level of a packaged product comprising the lower level elements within the product (Gu, et al., [B5]). Component-level electronics include packaged semiconductor devices, such as diodes, transistors, integrated circuits, and memory storage devices, and other packaged circuit elements such as inductors, resistors, and capacitors. The component level is referred to as Level 1.

A.5.4 Assembly level

The assembly level includes the printed circuit board and various board-specific features, such as interconnects, pads, plated through holes, vias, and traces, or analogous support structures and interconnects associated with a multi-chip or hybrid module. The assembly includes the components as well as the support structures and interconnects that provide mechanical stability and at the same time provide electrical and functional connectivity (Pecht, 2008 [B10]). The assembly level is commonly referred to as Level 2.

A.5.5 Sub-system level

The sub-system level for electronics can be defined on the basis of the functionality of a group of assemblies, such as printed circuit board assemblies (PCBAs), which are combined together in a specific geographical location. A sub-system may include the enclosure, PCBAs, and interconnections between PCBAs and associated electro-mechanical parts (Pecht, 2008 [B10]). The sub-system level is referred to as Level 3. Examples of the sub-system level include hard disk drives, line replaceable unit (LRU) boxes, electronic control units (ECUs), transmitters, receivers, and power supplies. Many sub-systems working together may be part of a complex system. The sub-system level is a level that is often employed by system architectures.

A.5.6 System level

The system level includes a more integrated and standalone functioning product. The system could be made up of many sub-systems or could be a functional combination of PCBAs and associated electro-mechanical components within an external enclosure. Examples of systems made up of sub-systems include radar installations, computers, and televisions. Examples of simple systems include digital timers and television remote controls. The system level is referred to as Level 4.

A.5.7 System-of-systems level

A.5.7.1 Description

"A system-of-systems is defined as a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities (DoD, 2008 [B9]). The system-of-systems level incorporates many systems into a complex overarching product. The system-of-systems level is referred to as Level 5. Examples of system-of-systems include aircraft, trains, automobiles, or sea-going vessels; aircraft communication, navigation, and identification systems (CNI); Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR); and also the external connections among integrated systems, such as computerized medical and health equipment.

Multiple system-of-systems could be connected to work together to generate a required function or operate as loosely connected entities carrying out similar functions. Some system of systems can be further classified as cyber-physical systems or swarm of systems. These are sub classifications of Level 5. Figure A.4 includes a Venn diagram that explains the concept.

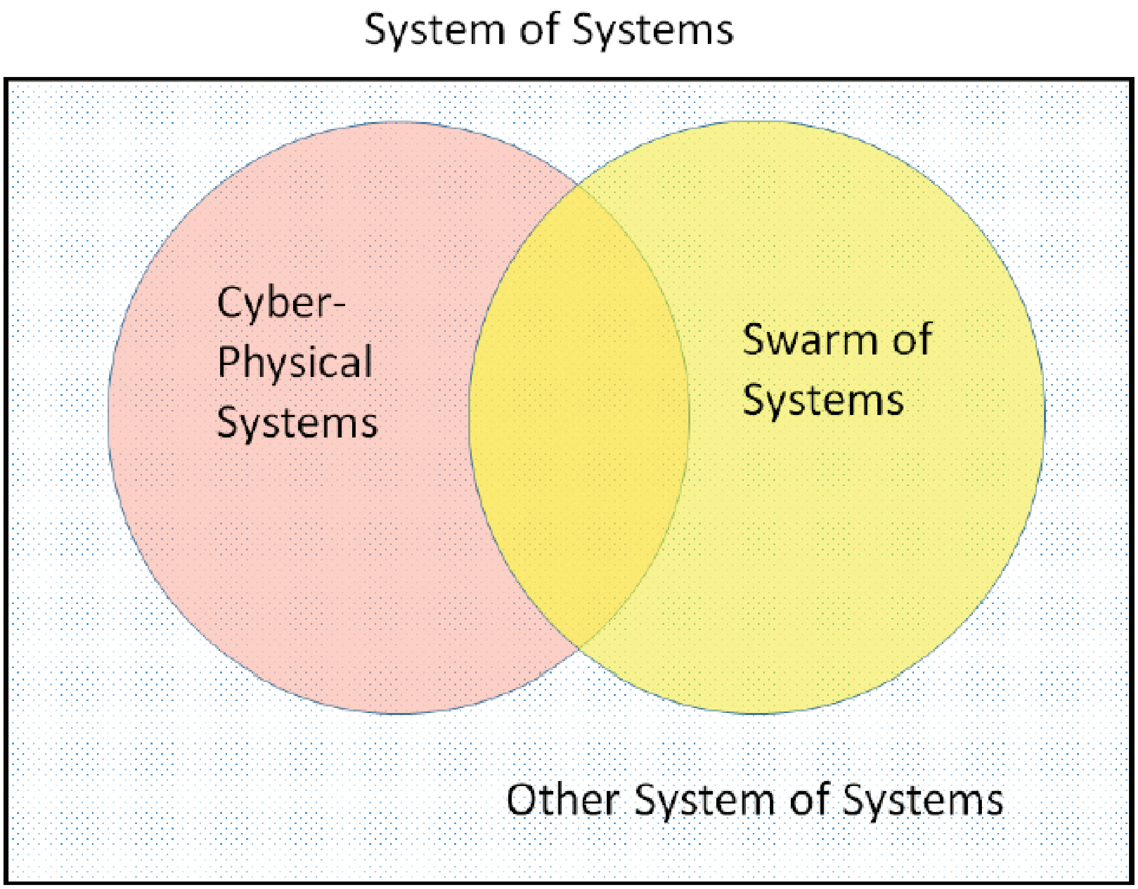


Figure A.4—Classification of system of systems

A.5.7.2 Cyber-physical systems

The cyber-physical system level includes networks that utilize a large number of distributed physical components and associated software to achieve specific tasks (Zhang [B17]). Cyber-physical systems interface the networks that bring computer processing, electronics, and mechanical systems together into a fully functional system. These systems employ sensors, integrated networks, and mechanically driven parts much like in robotics applications. The cyber-physical systems level is referred to as Level 5a.

Additional Information: Cyber-physical systems involve: network connectivity, combination of different system of systems with networks, performing a mission. Some cyber-physical systems are system-of-systems but not all, and vice versa.

Examples: Network/telecom systems, IEEE 802.11™, cloud, wireless protocols, aircraft systems; the electric power grid; and traffic control system over a grid of city streets.

A.5.7.3 Swarm of systems

Swarm of systems refers to system of systems and possibly even instances of cyber physical systems which are not organized, connected, arranged or combined in an overarching product or system. The contact between such system-of-systems respectively systems in a swarm could be loose and ad hoc. The systems could also be "members" in different swarms. A swarm of systems is classified as Level 5b.

Example: A swarm could be all cars on a section of a road in a certain time. May be there is a small bump in the road and this enables the detection of the step function response of each car. And because the load is known this information could be used for the PHM. Together with GPS information the condition of the road itself is measurable.

Example: UAVs, automobiles

Annex B

(informative)

Bibliography

Bibliographical references are resources that provide additional or helpful material but do not need to be understood or used to implement this standard. Reference to these resources is made for informational use only.

[B1] ABS Group, Inc., Root Cause Analysis Handbook: A Guide to Effective Incident Investigation, ABS Group, Inc. Rockville, MD: Risk & Reliability Division, 1999.

[B2] Blanchard, B. S., Logistics Engineering and Management, 4th Ed. Englewood Cliffs, NJ: Prentice Hall, 1992.

[B3] Dasgupta, A., R. Doraiswami, M. Azarian, M. Osterman, S. Mathew, and M. Pecht, "The Use of Canaries for Adaptive Health Management of Electronic Systems," ADAPTIVE 2010, IARIA Conference, Lisbon Portugal, Nov 21–26, 2010.

[B4] Feldman, K., T. Jazouli, and P. Sandborn, "A Methodology for Determining the Return on Investment Associated with Prognostics and Health Management," IEEE Transactions on Reliability, vol. 58, no. 2, pp. 305–316, June 2009, http://dx.doi.org/10.1109/TR.2009.2020133.

[B5] Gu, J., N. Vichare, T. Tracy, and M. Pecht, "Prognostics Implementation Methods for Electronics," Reliability and Maintainability Symposium, pp. 101–106. Orlando, FL, 2007.

[B6] IEEE Std 1413.1-2002, IEEE Guide for Selecting and Using Reliability Predictions Based on IEEE 1413, Institute of Electrical and Electronics Engineers Inc., 2003.

[B7] Lo, Y. and B. Stephen, Johnson, and J. Breckenridge, "Application of Fault Management Theory to the Quantitative Selection of a Launch Vehicle Abort Trigger Suite," IEEE Internation Conference on Prognostics and Health Management, Spokane, Washington, June 2014.

[B8] Mathew, S., "An Analytical Model for Developing a Canary Device to Predict Solder Joint Fatigue Failure Under Thermal Cycling Conditions, 2014 PhD. Dissertation, University of Maryland, College Park, MD.

[B9] Office of the Deputy Under Secretary of Defense for Acquisition and Technology, Systems and Software Engineering, "Systems Engineering Guide for Systems of Systems," Version 1.0. Washington, DC: ODUSD (A&T) SSE, 2008.

[B10] Pecht, M., Prognostics and Health Management of Electronics, Wiley-Interscience, New York, NY, August 2008.

[B11] Pecht, M. and A. Dasgupta, "Physics-of-Failure: An Approach to Reliable Product Development," Journal of the Institute of Environmental Sciences, vol. 38, pp. 30–34, September/October 1995.

[B12] Sandborn, P., Cost Analysis of Electronic Systems. Singapore: World Scientific, 2013, http://dx.doi.org/10.1142/8353.

[B13] Sandborn, P. and J. Myers, "Designing Engineering Systems for Sustainment," in Handbook of Performability Engineering, Misra, K. B., ed. London: Springer, 2008, pp. 81–103, http://dx.doi.org/10.1007/978-1-84800-131-2_7.

[B14] Saxena, A., J. Celaya, B. Saha, S. Saha, and K. Goebel, "Metrics for Offline Evaluation of Prognostic Performance," International Journal of Prognostics and health Management, vol. 1, no. 1, pages 20, 2010.

[B15] Saxena, A., J. Celaya, E. Balaban, K. Goebel, B. Saha, S. Saha, and M. Schwabacher, "Metrics for Evaluating Performance of Prognostic Techniques," International Conference on Prognostics and Health Management (PHM 2008), pp. 1–17, 2008, http://dx.doi.org/10.1109/PHM.2008.4711436.

[B16] Saxena, A., S, Sankararaman, and K. Goebel, "Performance Evaluation for Fleet and Unit-based Prediction Methods," Second European Conference of the Prognostics and Health Management Society, Nantes, France, July 8–10, 2014.

[B17] Zhang, Y., I.-L. Yen, F. B. Bastani, A. T. Tai, and S. Chau, "Optimal Adaptive System Health Monitoring and Diagnosis for Resource Constrained Cyber-Physical Systems," International Symposium on Software Reliability Engineering, Mysuru, Karnataka, India, pp. 51–6016–19, Nov 2009, http://dx.doi.org/10.1109/ISSRE.2009.21.

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