Towards a Capabilities Taxonomy for Prognostics and Health Management

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ABSTRACT

This communication proposes the development by the PHM Society of a classification or taxonomy for the skills needed for the prognostics and health management (PHM) field. This taxonomy is a set of descriptors for each skill for a chosen range of competency levels: entry, working and mastery. This communication defines a structure and process to ensure application to real needs by employers, practitioners and training developers. Preliminary results of the development of Analytics, Test and Experiment Design and Cost Benefit Studies sub-domains within the PHM field are reported based on workshops at the PHM 2012 and 2013 Annual Conferences. Steps for a way forward are proposed and mechanisms for interested parties to participate are suggested. The PHM Society's Education and Professional Development Committee would lead these efforts.

1. BACKGROUND

Prognostics and Health Management (PHM) is a diverse, multi-disciplinary domain with rapidly evolving capability needs. Initial education and training from many discipline entry points must be complemented by specialized and professional development over a PHM career.

The community's stakeholders in academia, industry and government require a stream of qualified practitioners with lifelong professional development.

The community has identified that benchmarks are needed for career planners, employers and training developers. For example, stakeholders are interested in facilitating transitions between competency levels.

Aligned with this scenario, the PHM Society has general objectives to:

- Promote the development, growth, and recognition of prognostics and health management (PHM) as an engineering discipline;
- Support PHM education by developing standard teaching curricula in the field; and
- Establish, develop, or adopt standards, methods, and metrics in PHM.

To accomplish these objectives the board of the Society has approved activities in this direction overseen by a committee on Education and Professional Development (EPD).

2. PROPOSAL

The proposed taxonomy or classification delineates PHM educational into skill and capability areas and by competency levels within each skill and/or capability. The taxonomy is captured in matrices with entries in rows and columns. Examples are listed below:

Skill/capability areas: PHM domains, e.g. signal processing, statistics, control systems, [as rows],
Competency levels: Entry, Working or Mastery for each [as columns].

Employers, practitioners, and training and professional course developers will use the taxonomy for hiring, training identification and selection, and training/course development.

Employers: A job description could be readily prepared to include a capabilities list from various areas with desired competency levels. Evaluation schemes could reference competency levels to be demonstrated or developed. Professional development transitions could be defined and matched to courses or in-house assignments.

Practitioners: To plan education and professional development progressions and understand skills and capabilities required.

Training and professional course developers: To identify niche course product areas. Specifically, descriptors would be commonly understood for likely pre-requisites available and new competencies to be acquired.

3. COMPETENCY DEFINITIONS

Competency definitions are required for this use of such a taxonomy. Pedagogical references provide a basis for this selection of a working set (Carnegie Mellon University, 2013) based on fundamentals developed by Bloom (1956).

The progression of complexity is typical within the hierarchies used for taxonomies. The National Research Council Canada (NRC) has developed a soft skill hierarchy (NRC, 2013). As an example, the creative thinking skill is defined to respond to challenges with innovative solutions, products or services by questioning conventional means, using intuition, experimentation and fresh perspectives. Five levels of competency with descriptors are provided for this skill:

Level 1: Understands how to solve problems

- Uses common sense and knowledge to identify underlying issues and to solve problems.
- Uses appropriate problem-solving techniques.

Level 2: Identifies existing solutions

- Reviews existing options, concepts and approaches, and identifies one(s) that will work in the situation at hand.
- Stands back from a problem and observes patterns and interrelationships in data to see where problems or discrepancies arise.
- Recognizes and assesses several likely causes or ways of interpreting available information.
- Recognizes when a new approach is needed to solve a problem.
- Solves complex problems through application of existing theories or explanations.

Level 3: Modifies existing solutions

- Questions traditional solutions and uses unconventional methods to find solutions.
- Thinks about problems from a new perspective.
- Solves problems by applying ideas from other disciplines or fields of research.

Level 4: Creates new solutions/concepts

- Thinks several steps ahead in deciding on best course of action (anticipates likely outcomes).
- Creates, assesses and applies new concepts, theories, approaches and/or solutions.
- Solves complex or inter-related problems through developing new theories, explanations or applications.

Level 5: Impacts a field of science/technology

- Develops new theories and applications with revolutionizing or wide-ranging impacts.

As an alternative to this soft skill hierarchy, a technical skill can also be categorized by breadth of application (Reichard, 2012), in a three level approach:

1. Engineering and technical contribution at the subsystem level is required.
2. The conversion of concepts to subsystems and systems, major system design and/or technical leader in multiple projects.
3. A developer of engineering concepts, major system design, and/or technical leader in multiple programs. A principal contributor in systems design, systems engineering, concept development, and project reports.

For the PHM taxonomy considered here, we have decided to use three levels that incorporate important aspects of these two above approaches:

1. Entry Level: Understands, selects, interprets and applies basic concepts and known methods. May work at the sub-system level.
2. Working Level: Analyses and solves complex problems by combining or extending existing methods. Likely integrates and validates at the system level.
3. Mastery Level: Evaluates, innovates, synthesizes and validates new methods through unique, often multi-disciplinary insights.

Application of skills may include analysis, design, build/implement and test for equipment, hardware and software.

4. PHM SKILLS AND CAPABILITIES

Compiling a list of possible skills for PHM practitioners is challenging because the field is multi-disciplinary. A generic IVHM taxonomy has been proposed by Jennions (2011). He identifies key high-level IVHM *system* components: service offerings, business, systems design, architecture, analytics, technologies, applications and support.

This work aims to extend existing taxonomies to meet the multiple stakeholder needs (Section 2) with a comprehensive list of *skills*. Firstly, we propose to subdivide skills and capabilities as follows:

1. Domain: major category of a technical skill or competency
2. Sub-domain: constituent sub category that could be associated with a stream of graduate courses
3. Specialty: subject that could constitute a specific course

While it is acknowledged that there are overlaps between the domains, a working list of key PHM domains and sub-domains (with some sample specialties) is proposed:

1. System physical modeling
   a. Fluid mechanics- aerodynamics, hydraulics/hydrodynamics
   b. Electrical/Electronics
   c. Mechanical
   d. Structural
   e. Thermodynamics
   f. Data driven- bond graphs
   g. Hybrid approaches
2. Data Modeling
   a. Parametric
   b. Non-parametric
   c. Hybrid
3. Analytics
   a. Data pre-processing
   b. Feature extraction
   c. Feature selection
   d. Classification- methods, metrics
   e. Regression- methods, metrics
   f. Optimization- methods, metrics
   g. Model Fusion
   h. Anomaly Detection
   i. Fault Isolation- observability, coverage
   j. Prognostics- specialized methods, metrics (e.g. latency)
   k. Data Fusion by data types
   l. Special Issues with time series data
   m. Special Issues with nominal data types
   n. Reasoners- meta-classifiers, Bayesian, fuzzy logic

Note: Diagnostics is considered to comprise e to i and n

4. Test and Experimental (Design and conduct)
   a. Data acquisition- steady state, targeted, transient, dynamic
   b. Inspection/evaluation- NDI/E
   c. Uncertainty analysis
   d. Sensor
   e. Data reduction
   f. Data transmission
   g. Fault implantation
5. Software Systems
   a. Architecture- standards
   b. Real time system
   c. User interfaces
   d. Software system integration (up to enterprise integration)
   e. Data compression
6. Hardware Systems
   a. Off board- standards
   b. On board- standards
   c. Sensors- design, specification, integration
7. Life Cycle Analysis
   a. Root cause analysis
   b. Fault Tree Analysis
   c. Functional Hazard Analysis
   d. Fault accommodation
   e. Trade studies
   f. Reliability
   g. Availability
   h. Maintainability
   i. FMECA- FM, E, C
   j. Logistics
8. Verification and Validation
   a. Methods
   b. Maturation
9. Human Factors
   a. Needs analysis- standards
   b. Usability - standards
10. Systems Engineering
    a. Usage Monitoring
    b. Health Management- State Awareness, Diagnostics, Prognostics, Decision Support, e.g. Contingency –based Management
    c. Autonomous systems
11. Cost Benefit Analysis
    a. Needs analysis
    b. Risk Analysis
    c. Metrics, uncertainty/confidence and evaluation
    d. Business case
    e. Support Service/Performance Based Logistics approaches
12. Certification
    a. Standards
    b. Safety Status Analysis
    c. Risk management
    d. Post certification management
13. Standards

5. SAMPLE CAPABILITIES-COMPETENCY MAPPING

Here we take a practitioner skills/capability viewpoint as opposed to the IVHM system components view. This approach follows a general model: application of existing tools at the entry level, adaptation at the working level and customization or new methods at the mastery level.

A sample taxonomy entry is provided in Table 1 for the Analytics domain and Diagnostics sub-domain, with three competency level descriptors. Additional rows of descriptors could be added to Table 1 to accommodate the complexity of the analysis, and hands-on or other appropriate skills

Specialty	Entry Level descriptors	Working Level descriptors	Mastery Level descriptors
Methods	Apply existing single and multi-disciplinary methods …	Assess shortcomings in existing methods- adapt/hybridize methods to suit …	Develop new methods from novel physics or mathematical insights …
Metrics	Apply appropriate existing metrics …	Adapt metrics to complex system evaluation …	Devise and approve system level metrics …

Table 1. Sample Taxonomy Entry

6. DEVELOPMENT OF TAXONOMY

The PHM Society Education and Professional Development Committee sponsored a workshop at the PHM 2012 Annual Conference to develop the concept described above. Three significant domains were selected, each had a broad based group examine the sub-domain list and also to draft competency descriptors. While these resulting products for Analytics, Test and Experiment Design and Cost Benefit Analysis are neither complete nor final, it was felt that the developing a 'straw man' version would be helpful to the Society to assess the feasibility of producing a complete taxonomy. Details follow for these workshop products.

6.1. Domain 1- Analytics

The working group at the PHM 2012 conference agreed to accept the sub-domains in section 4 above. However, they considered the prognostics sub-domain separate and were not able to address it in the time available. They proposed working versions of the competency descriptions for most of the sub-domains in that list and added some specific specialties within some sub-domains. For a number of the specialties/analysis tools they chose the same generic descriptors. Annex 1 provides the results. In general, they proposed application of existing tools at the entry level, adaptation at the working level and customization or new methods at the mastery level.

6.2. Domain 2- Test and Experiment Design

The working group at the conference added additional sub-domains: integration, fault injection/insertion, data validation, data reduction and data management. They chose not to add specialties in the limited time available. The descriptors addressed a number of diverse skills and capabilities across the hardware/software/sensor scope of this domain. Details are provided in Annex 2.

6.3. Domain 3- Cost Benefit Analysis

The group who discussed the Cost Benefit Analysis domain proposed adding sub-domains for asset management, maintenance and the effect of prognostics management, and business versus customer perspective. It was also suggested that metrics, uncertainty/confidence and evaluation might be considered as specialties within the risk analysis sub-domain. Details are provided in Annex 3.

7. CONCLUSIONS AND WAY FORWARD

The need for a broadly applicable PHM taxonomy has received a preliminary validation through a limited workshop process at the PHM 2012 Annual Conference. The three classes of users were confirmed. The general form and a working set of definitions have been developed and reviewed. Draft taxonomies for three PHM domains have been proposed for further development through either workshops or specialists. The appropriate number and level of detail for the specialties is yet to be determined.

The PHM Society Education and Professional Development (EPD) Committee is coordinating actions to:

1. Prepare and circulate a Working Model of a PHM Capabilities Taxonomy- this communication document.
2. Conduct Conference Workshops covering evolving issues and the taxonomy approach- planned for PHM 2013.
3. Develop the inputs for this taxonomy from subject matter experts.
4. Compile sources for entry-level skills.
5. Compile courses available for transitions across competency levels from existing materials and programs in various organizations.
6. Identify gaps in current post-secondary and graduate continuing education materials and opportunities.

Linkages with the SAE HM-1 committee will ensure that this work is complementary to other efforts. In the longer term, the PHM Society expects to work with appropriate organizations to develop needed materials and opportunities. To that end, the PHM Society is establishing a comprehensive set of technical co-sponsorships with major organizations.

Interested parties are invited and encouraged to contribute by contacting one of the authors or participating in the on-line forum at www.phmsociety.org/forum/577.

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BIOGRAPHIES

Jeff Bird is currently a consultant with TECnos Consulting Services, Ottawa, Canada. His present avocations include advancing the art, science and business of prognostics and health management in diverse fields. Specifically, he leads PHM Society board initiatives in Education and Professional Development as well as Standards. He recently completed one career spanning 30 years as a Research Officer at the Gas Turbine Laboratory of the National Research Council Canada. His published research there included gas turbine dynamics and performance, health monitoring and management, adverse environments, and uncertainty. Previously he worked as an Operational Research officer in the Department of National Defence where he enjoyed contributing to airlift and search and rescue planning. He studied at the University of Toronto (Engineering Science- Aerospace) and at Carleton University (Mechanical, Aerospace and Systems)

Nancy Madge is a partner at TECnos Consulting Services. She specializes in curriculum development for adult learning and training in industrial and professional settings. Over some 28 years, she has developed user needs definitions, course designs and materials for participants and instructors across diverse applications such as telephony, calculus, tax law, computer systems and process operation. Her Bachelor's qualifications are in Music Education at the University of Western Ontario complemented by Master's work in curriculum design at Brock University. She completed integrated arts and education coursework towards a doctorate at the University of Toronto's Ontario Institute for Studies in Education**.**

Dr. Karl Reichard is a Research Associate at the Applied Research Laboratory at The Pennsylvania State University and Deputy Department Head of the Advanced Sensors and Controls Department in the Multisensor Processing Division. He has more than 15 years of experience in the development of advanced sensors, measurement systems, and signal processing algorithms. An Assistant Professor of Acoustics at Penn State and Head of the Condition-Based Maintenance Department at the University's Applied Research Laboratory, Dr. Reichard leads advanced research and development efforts in embedded systems, electro-optics, intelligent acoustic and vibration sensors, and signal processing and classification algorithms for active noise and vibration control, manufacturing machinery monitoring, and surveillance systems. Prior to joining Penn State ARL in 1991, he was employed by the U.S. Army Aberdeen Proving Grounds and Virginia Polytechnic Institute and State University, his alma mater. Dr. Reichard has published more than 25 papers in refereed journals, conference publications, and technical reports. Dr. Reichard serves as Associate Editor of the International Journal on Prognostics and Health Management.

Annex 1: Draft Taxonomy for Analytics Domain

Sub-domain	Specialty	Entry Level descriptors	Working Level descriptors	Mastery Level descriptors
Diagnostics	Methods	Apply existing single and multi-disciplinary methods Other	Assess shortcomings in existing methods-adapt/hybridize methods to suit Other	Develop new methods from novel physics or mathematical insights
	Metrics	Apply appropriate existing metrics	Adapt metrics to complex system evaluation	Devise and bring into acceptance system level metrics
Data Pre-Processing	De-noising / Outlier Detection	Ability to implement and apply algorithms. Ability to understand algorithms	Ability to decide which algorithms to apply, choose parameters for analysis, modify existing algorithms	Develop new techniques and approaches based on mathematical insight
	Transformation			
	Database Design	Understand and use database	Ability to choose appropriate database design from existing designs and match tools to PHM requirements	Customization of database, database design, optimization
	Special Issues with nominal data types			Ability to recognize and apply appropriate processing techniques to accommodate differences in data types
Feature Extraction				
Feature Selection	Physics / Engineering Approaches	Works with SME to identify techniques and applies/implements	Understands how to decompose problem/system and identifies appropriate SME	Develop engineering or physical models and new techniques
	Statistical Approaches	Ability to implement and apply algorithms. Ability to understand algorithms	Ability to decide which algorithms to apply, choose parameters for analysis, modify existing algorithms	Develop new techniques and approaches based on mathematical insight. Ability to work cross domain with Machine Learning or Engineering/physical approaches
	Machine Learning	Ability to implement and apply algorithms.	Ability to decide which algorithms to apply, choose parameters for	Develop new techniques and approaches based on

Sub-domain	Specialty	Entry Level descriptors	Working Level descriptors	Mastery Level descriptors
		Ability to understand algorithms	analysis, modify existing algorithms	mathematical insight. Ability to work cross domain with statistical approaches or Engineering/physical approaches
Classification	Cluster Analysis / Unsupervised Learning	Ability to implement and apply algorithms. Ability to understand algorithms	Ability to decide which algorithms to apply, choose parameters for analysis, modify existing algorithms. Knows multiple techniques	Develop new techniques and approaches based on mathematical insight. Increased breadth of knowledge
	Supervised Learning	Ability to implement and apply algorithms. Ability to understand algorithms	Ability to decide which algorithms to apply, choose parameters for analysis, modify existing algorithms. Knows multiple techniques	Develop new techniques and approaches based on mathematical insight. Increased breadth of knowledge
	Statistical Approaches	Ability to implement and apply algorithms. Ability to understand algorithms	Ability to decide which algorithms to apply, choose parameters for analysis, modify existing algorithms. Knows multiple techniques	Develop new techniques and approaches based on mathematical insight. Increased breadth of knowledge
	Metrics	Apply appropriate existing metrics	Adapt metrics to complex system evaluation	Devise and bring into acceptance system level metrics
Regression	Statistical Techniques	Ability to implement and apply algorithms. Ability to understand algorithms	Ability to decide which algorithms to apply, choose parameters for analysis, modify existing algorithms. Knows multiple techniques. Ability to understand and apply hybrid techniques	Develop new techniques and approaches based on mathematical insight. Increased breadth of knowledge.
	Machine Learning	Ability to implement and apply algorithms. Ability to understand algorithms	Ability to decide which algorithms to apply, choose parameters for analysis, modify existing algorithms. Knows multiple techniques. Ability to understand and apply hybrid techniques	Develop new techniques and approaches based on mathematical insight. Increased breadth of knowledge
Optimization	Gradient-based	TBD	TBD	TBD

Sub-domain	Specialty	Entry Level descriptors	Working Level descriptors	Mastery Level descriptors
	Evolutionary	TBD	TBD	TBD
	Operations Research	TBD	TBD	TBD
Model Fusion		Applies existing algorithms. Understanding of basic voting techniques	Ability to decide on which algorithms to employ, understanding of machine learning and statistical techniques	Development of new techniques
Fault Detection and Isolation (includes anomaly detection)		Ability to implement and apply algorithms. Ability to understand algorithms	Ability to decide which algorithms to apply, choose parameters for analysis, modify existing algorithms. Knows multiple techniques	Develop new techniques and approaches based on mathematical insight. Increased breadth of knowledge
Data Fusion	Data Level	TBD		
	Feature Level	TBD		
	Decision Level	TBD		
Special Issues-Time Series Data		TBD		
Reasoners	Bayesian	Ability to implement and apply algorithms. Ability to understand algorithms	Ability to decide which algorithms to apply, choose parameters for analysis, modify existing algorithms. Knows multiple techniques. Ability to understand and apply hybrid techniques	Develop new techniques and approaches based on mathematical insight. Increased breadth of knowledge
	Expert Systems	Ability to implement and apply algorithms. Ability to understand algorithms	Ability to decide which algorithms to apply, choose parameters for analysis, modify existing algorithms. Knows multiple techniques. Ability to understand and apply hybrid techniques	Develop new techniques and approaches based on mathematical insight. Increased breadth of knowledge
	Fuzzy Logic	Ability to implement and apply algorithms Ability to understand algorithms	Ability to decide which algorithms to apply, choose parameters for analysis, modify existing algorithms. Knows multiple techniques. Ability to understand and apply	Develop new techniques and approaches based on mathematical insight. Increased breadth of knowledge

Sub-domain	Specialty	Entry Level descriptors	Working Level descriptors	Mastery Level descriptors
			hybrid techniques	
	Meta-Classifiers	Ability to implement and apply algorithms. Ability to understand algorithms	Ability to decide which algorithms to apply, choose parameters for analysis, modify existing algorithms. Knows multiple techniques. Ability to understand and apply hybrid techniques	Develop new techniques and approaches based on mathematical insight. Increased breadth of knowledge
Fault Isolation		Ability to implement and apply algorithms. Ability to understand algorithms	Ability to decide which algorithms to apply, choose parameters for analysis, modify existing algorithms. Knows multiple techniques. Ability to understand and apply hybrid techniques	Develop new techniques and approaches based on mathematical insight. Increased breadth of knowledge
Prognostics	Statistical Techniques	TBD		
	Machine Learning	TBD		
	Physics- Based	TBD		

Annex 2: Draft Taxonomy for Test and Experiment Design Domain

Sub-domain	Entry Level descriptors	Working Level descriptors	Mastery Level descriptors
Design of Experiment (DOE)	Apply fully specified DOE	Develop an experimental design: replicates, environment, initial conditions	Modify DOE process/constraints/metrics
Data Acquisition	Program Lab view or equivalent software Set up and assemble physical devices Assign sensors to appropriate hardware	Select hardware and software Define appropriate shielding and signal methods, alignment and calibration Synchronize signals from multiple sensors Define appropriate telemetry or remote methods	Design and apply adaptive, multidiscipline, multi bandwidth methods
Inspection/ Evaluation	Apply known techniques at sub system level, non-destructive processes	Select appropriate technique(s) for a given component Identify failure mode characteristics Interpret results	Develop novel techniques that combine multi-physics methods
Measurement Uncertainty Analysis	Estimate elemental contributions for conventional measurements	Develop propagated estimates for parameters made up of many elements Develop calibration hierarchies Develop elemental estimation methods for complex measurements	Devise new estimation and validation experiments Develop novel estimation methods for complex systems
Sensors	Install sensors for basic measurements Interpret output signals	Select sensors to meet detailed requirements that are developed at a system level: resolution, bandwidth and repeatability	Design a new sensor from physic principles Interpret complex interactions of sensors with environment
Integration	Design and assemble complex hardware and software experimental setups Select and source components	Define and prioritize essential integration metrics and functions to achieve high level objectives: physical, mechanical, safety and, reliability Design to meet cost effective criteria and appropriate complexity	Optimize design for complex and conflicting constraints Develop scalability methods
Fault injection/ Insertion	Conduct fully specified fault injection tests Validate test results against baseline or reference data	Apply existing fault modes in destructive and non-destructive ways Develop controlled simulations with system modifications:	Design fault initiation and propagation methods Design and validate accelerated/aging test methods

Sub-domain	Entry Level descriptors	Working Level descriptors	Mastery Level descriptors
		simple biases and ramps Define limiting assumptions Apply relevant noise simulations Define and apply installation and environment effects Interpret usage information to incorporate realistic test cases	Design and develop correlation and validation methods
Data Validation	Conduct functional and reality checks for conventional measurements	Design and conduct functional and reality checks for transient and dynamic data involving complex sensor suites Identify sources of error or ambiguity in data	Design validation schemes for multidisciplinary processes
Data Reduction	TBD		
Data Management	Manage multiple data sets ensuring providence and database compilation	Develop buffer and transmission designs Define storage providence and database implementation methods	

Annex 3: Draft Taxonomy for Cost Benefit Analysis

Sub-domain	Entry Level descriptors	Working Level descriptors	Mastery Level descriptors
Needs Analysis	Review requirements and stakeholders How to satisfy requirements	Refining requirements Review and refine stakeholders	Defining requirements Define new stakeholders
Risk Analysis	Identify known solutions likelihood of success and consequence Current company capabilities	Assess technology readiness level Identify risks and consequences	Analyze risk of novel approaches
Metrics, Uncertainty/ Confidence and Evaluation (part of risk analysis?)	Capture data to facilitate evaluation	Evaluating performance against metrics	Setting metrics in conjunction with stakeholders
Business Case	Given a business case template, enter applicable data	Research existing business cases, find applicable model Apply and analyse impacts	Create a business case model to use in a new novel scenario Design simulations to demonstrate/prove case
Support Service/ Performance Based Logistics approaches	TBD		
Return On Investment	Plug in data to existing formulas	Identify required changes to business models Define "what if" scenarios	Creating new business models
Asset Management	TBD		
Maintenance and the Effect of Prognostics Management	TBD		
Business versus Customer Perspective	TBD		