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Methodology and Framework of a Cloud-Based Prognostics and Health Management System for Manufacturing Industry

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Prognostics and Health Management (PHM) as a research discipline has been extensively studied in recent years, with many sophisticated techniques and intelligent algorithms developed for machinery data analysis, health assessment and decision making. PHM solutions for typical components such as roller bearing and machine tool have grown and proved to be reliable enough for industrial application. However utilization of PHM solutions in industry is still much limited due to high research, development and implementation costs. Such limitations are more severe in smaller scale factories and workshops where no ample resource is available for implementing PHM systems. Efforts have been made to tackle such issue, for instance, Watchdog Agent® Toolbox developed by the IMS Center enables faster deployment of PHM solutions through algorithm modularization and standardization. With advantages that can be delivered with the emerging cloud computing paradigm, a cloud-based prognostics and health management system for manufacturing industry has been developed based on Watchdog Agent® tools and the ideology of *PHM as a Service*. In addition to traditional data acquisition and management functions in a machine condition monitoring system, the cloud based PHM platform is able to further provide on-demand, customizable and low-cost data analysis service. Machinery data accumulated within the cloud system further enables more advanced services such as machine-to-machine comparison, data mining and knowledge discovery.

1. Introduction

Prognostics and Health Management (PHM) for machinery can provide machine users and factory managers the abilities to ensure product quality, perform just-in-time maintenance, avoid catastrophic failure and minimize equipment downtime. Due to such benefits, PHM has gained more and more attention in both academia and industry. Extensive researches have been carried on by universities and research institutes for developing algorithms and solutions for system diagnosis and prognosis. A typical PHM process usually involves a training stage, where intelligent algorithms are used to discover and learn machine degradation related patterns and trends from historical data; and a testing stage, where the trained model is applied to new machine condition data for health assessment and prediction. Among all the well-established PHM technologies, Watchdog Agent® Toolbox developed by the IMS Center provides a set of intelligent algorithms such as Neural Network, principal component analysis (PCA), among others, to convert data/information from multiple sensors to valuable health assessment and prediction results. Several case studies on commercial elevators and rotating machinery have been demonstrated to prove the effectiveness of the PHM algorithms in the toolbox (Djurdjanovic, Lee et al. 2003). Complete PHM solutions for certain mechanical components have also evolved into highly reliable, automated and standard procedures that can be quickly deployed with little customization required. For example, (Randall and Antoni 2011) introduced a generalized workflow for detecting early stage bearing faults that can be applied to roller bearings in a wide range of application and rotating speed.
From an implementation point of view, generally there are two ways for deploying a PHM system: standalone systems and remote monitoring servers. For the former case, an embedded system or a local server, depending on the required computational power, is used for data acquisition and analysis. The

standalone PHM system directly connects to the machinery that needs to be monitored and thus is easy to install and flexible to perform real-time PHM tasks (Chen, Yang et al. 2012). Standalone systems however suffer shortcomings such as limited processing speed, data storage capacity and maintainability of both hardware and software when number of machine increases. With the growth of information technologies more and more monitoring systems adapt the latter case, where data from multiple machines is collected and sent to remote servers for centralized data management and analysis. Centralized server provides better accessibility of machine data and more efficient data analysis specially for monitoring distributed facilities. As data connectivity is becoming less and less a problem, network enabled equipment monitoring systems appear to be more popular nowadays for machinery data analysis and asset management purposes (Wang, Chen et al. 2010; Yazidi, Henao et al. 2011).
However, despite those attractive benefits one can get from PHM systems, implementation of PHM technology is still not widely seen in manufacturer's production floor, which is mainly caused by high costs for developing and maintaining PHM systems. Currently developing a reliable PHM strategy still requires a full development cycle including testing, data acquisition, algorithm/software development and validation. Such development cycle requires much time and resource that can only be afforded by research institutes in universities or big companies. Data management and software maintenance during usage also create great IT burden for companies. Due to the aforementioned reasons most of the industry still relies on the traditional maintenance strategies, such as fail-and-fix maintenance and preventive maintenance.
On the other hand, technological advances and the new ideology, namely *X as a Service*, brought by the emerging cloud computing paradigm are opening new opportunities to tackle existing hurdles for implementation of PHM systems. Besides better connectivity and maintainability of IT infrastructure, cloud computing enables on-demand and scalable computing resources for data management and analysis functions. Furthermore, with modularized Watchdog Agent® tools, an easy-to-configure and shareable PHM service in a cloud environment cab be established. Within the cloud based PHM system, previously developed PHM solutions (e.g. remaining useful life prediction programs for roller bearings, machine tools) are formatted and converted in to "workflow templates" that can be easily reused by other industrial users who have similar needs. With ubiquitous data collection, modularized PHM algorithms and shareable PHM workflow, the cloud-based PHM system is able to provide low-cost, on-demand yet reliable PHM service to manufacturing industry.

2. Utilizing cloud computing for PHM services

Cloud computing has drawn much attention as a new emerging business model. Cloud computing as an IT paradigm is believed to be a successor of other computing models such as grid computing and cluster computing that combine distributed physical IT infrastructure into unified computing resources. Within the cloud computing model several key technologies including IT infrastructure virtualization and networking techniques are integrated together to further create a highly scalable, flexible, easy-to-access and on-demand pool of IT resources (e.g. servers, data storage, software applications, etc.) (NIST 2011). Cloud computing is first extensively used for enabling new ways to develop business services, such as scalable social network sites and online data storage/share services. The scalability of cloud computing makes algorithms in the cloud easy to expand as user group grows, which previously had to be considered and solved by developers in the early design stage. Another technique enabled by cloud computing is called "whole system snapshot exchange" (Dudley and Butte 2010), where a preconfigured operating system with necessary software installed for a certain purpose (e.g. data analysis, web service, etc.) can be easily duplicated into a new server instance so that the computation can be more reproductive. Such mechanism is also useful for sharing data analysis workflows within the scientific research community. On the other hand, the capability of provisioning on-demand computing power offered by cloud computing is also considered very suitable for large scale data storage and analysis (Bennett, Grossman et al. 2010).
Cloud computing paradigm offers an easier and more efficient way to transform existing PHM algorithms and workflows in academia into practical industrial-orientated services. In this paper, the methodology for adapting PHM systems in to a cloud environment, where PHM solutions are more reconfigurable, reproductive and easy to be implemented in manufacturing industry, is introduced. For the cloud based PHM system, *Infrastructure as a Service* (*IaaS*) model is used as the basic platform, where virtual machines (instances) are provisioned as PHM servers per user's request. *IaaS* is one of the implementation models provided by cloud computing along with *Platform as a Service* (*PaaS*) and *Software as a Service* (*SaaS*) (Armbrust, Fox et al. 2009). Comparing with *PaaS* and *SaaS*, *IaaS* offers more flexibility by providing full control of virtual machines including software applications, data storage and networks. By adapting cloud computing with the existing Watchdog Agent® Toolbox, a cloud based

PHM system for manufacturing industry can be established. Detailed structure and methodology for the cloud based PHM system are further explained in section 3.

3. Framework for cloud-based PHM system

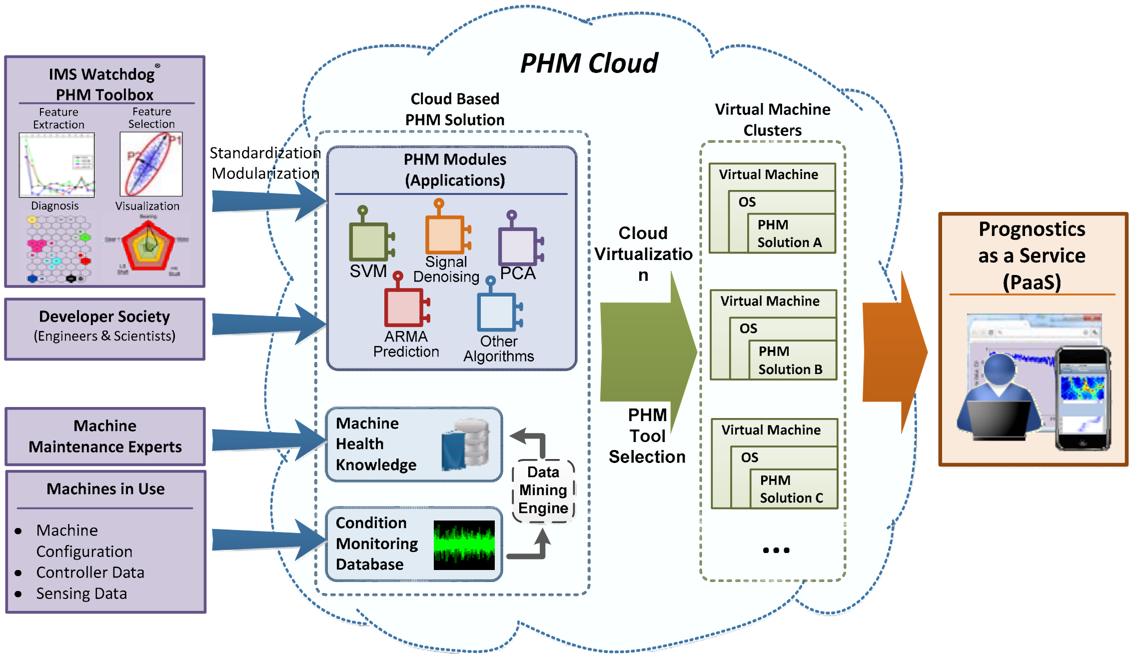

Figure 1: Overall methodology for the cloud-based PHM system

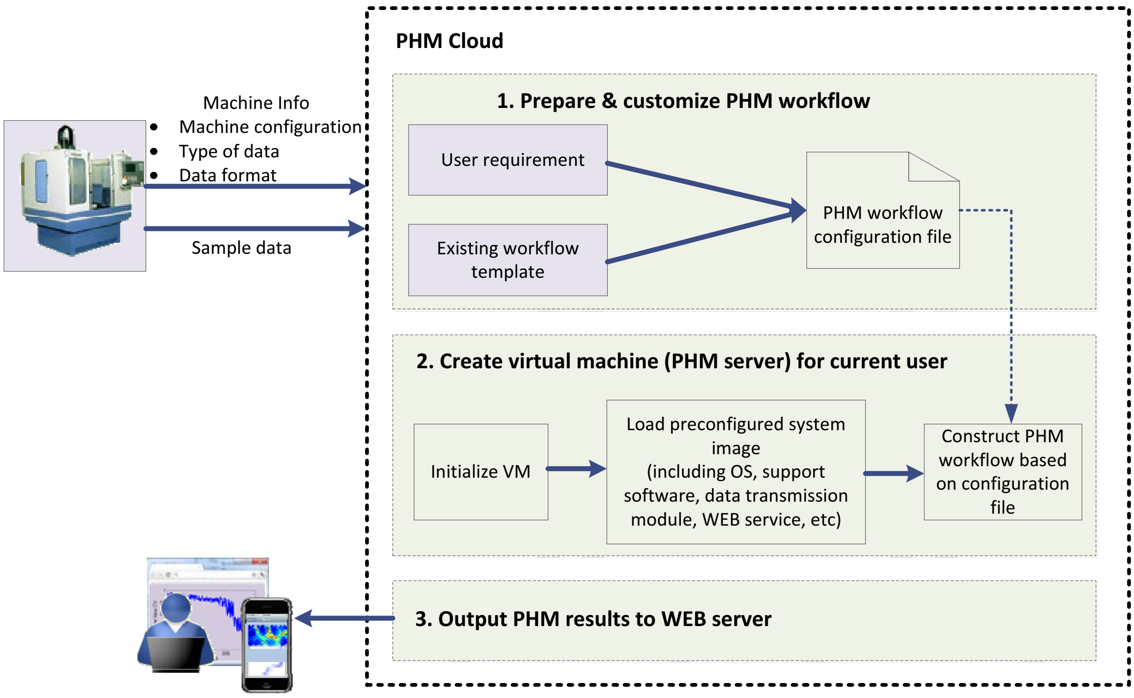

Figure 2: Provisioning one virtual machine as a PHM server for a new user

The overall methodology for cloud-based PHM system based on *IaaS* is shown in Figure 1. The system utilizes modularized PHM algorithms from IMS Watchdog Agent® Toolbox as basic components to form different PHM workflows. Workflows for typical components and mechanical problems are summarized and saved in a knowledge base that can be later used as templates for similar problems. Based on specific need (e.g. type of component for monitoring, type of data available, etc.) certain workflow will be selected and provisioned into a virtual machine as an individual PHM server dedicated to an industrial user (see Figure 2). The PHM server also consists of preconfigured database engine and a web server so that user can upload new condition monitoring data and retrieve PHM results using Web browsers and smart mobile devices. The system can be further broken down into several key steps.


```
<CloudConfig Name="TCM" Version="1.0" Application="ToolConditionMonitoring">
  <MasterProgram Name="MasterProgram_MatlabV1"/>
  <Info fs="1000" Description="TCM_Data_From_ServBox" ToolCount="1"/>
  <Steps>
    <Step ID="1" Type="Func">
      <Function Name="TCM_ParseData"/>
      <ParameterIn Type="Variable" Value="0|1"/>
      <ParameterIn Type="Value" Value="file_range = 1:5, folder_name=
Fun_TCM\TCM_data_files"/>
    </Step>
    <Step ID="2" Type="Func">
      <Function Name="VIB_FeatureExtraction"/>
      <ParameterIn Type="Variable" Value="1|1"/>
      <ParameterIn Type="Value" Value="data_column_ID=2 3,raw_features=100"/>
    </Step>
    ... ...
```


Figure 3: Configuration file for a PHM workflow

Standardization and modularization of PHM algorithms: a basic principle of formulating a workflow is that the inputs and outputs of each component in the workflow should be uniformly defined so that the steps can be seamlessly connected. PHM algorithms in Watchdog Agent® Toolbox are already categorized into several clusters (steps) based on functionality including health feature extraction, feature selection, health assessment and prediction. Interface standards for tools in each cluster are then defined so that as long as the standard is followed all algorithms in the same category are interchangeable. With standardized PHM algorithms, PHM workflows can be easily formulated by selecting proper algorithms for each step (training, testing, prediction, etc.) for different problems. Furthermore, with interface standards published to other engineers and scientists, more PHM algorithms can be added to the PHM cloud as standardized analytical modules.

PHM tool selection and workflow formulation: workflows are described and saved using PHM workflow configuration files which are based on the standard XML format (see Figure 3). The configuration file enables PHM workflows to be easily shared and modified among cloud PHM users. For new cases where no proper workflow can be used, PHM experts will select proper tools and formulate a new workflow based on properties of the machinery and condition monitoring data.

Initialization of PHM server: finally within the *IaaS* structure, for each new user cloud controller will provision a virtual machine (VM) and assign proper computing resources including number of CPUs, size of memory and hard disk based on amount of data storage and analysis capacity based on user requirements (see Figure 2). The newly initialized VM server will then load preconfigured system image that consists of necessary runtimes, software, database engine and a Web server to perform basic data acquisition, storage and management functions. To add PHM capabilities, specified PHM algorithms will be integrated to form an executable workflow according to the workflow configuration file. Workflows are designed to interface with database in the VM, so that it could read raw condition monitoring data, perform data analysis and then write health information back to database, which is displayed by Web interfaces per user's request (see Figure 4).

4. Advances of the proposed system

In this section advances of the proposed cloud based PHM system are further highlighted as following:

4.1 Minimal IT burden for PHM users

Cloud computing provides computing as a service with improving information security guarantee (Lombardi and Di Pietro 2011), which means users are not required to invest any IT hardware or software for implementing PHM systems. Moreover the proposed cloud base PHM system utilizes standardized data transmission protocols such as MTConnect (MTConnect 2013) so that proprietary standards defined by different machine OEMs could be uniformly accessed without having to modify data analysis algorithms.

On the other hand, from a system management point of view, PHM servers in the PHM cloud are based on same structure (image) yet independent to each other. Such mechanism ensures better system manageability as well as stability. Within the cloud environment any system update (e.g. improvement of web server, database structure, etc.) can be easily done by modifying system image file, while possible errors caused by PHM data analysis workflow will be constrained within separated virtual servers.

4.2 Share & improvement of PHM solutions

Many PHM algorithms for data analysis already exist, yet a major question for developing a PHM solution is which algorithms/tools to select for each specific case. Decisions like this usually have to be made according to considerations including type of problem (e.g. vibration related, torque related, etc.), type of data, noise level, among others. As a consequence, PHM experts are needed to perform tests and validations, to determine which algorithms to be used, for each problem. Afterwards when another piece of machinery (sometimes even with very similar conditions) requires PHM services, most probably the same procedure will be conducted again because of lack of sharing PHM solutions among research institutes or companies. With the PHM workflow configuration file and standardized PHM tools, the cloud based PHM system provides the capability of sharing PHM solutions and further enables faster-deployment and low-cost PHM services.

4.3 Coupled model for machinery

Ubiquitous connectivity of cloud computing allows the data/condition of the machine to be logged anytime throughout its whole lifecycle. Coupled model is a PHM approach that records data and status of machines through its whole life span including manufacturing, assembly, shipment, actual usage and maintenance actions, so that the status and propagation of any design defect, manufacturing error and/or component degradation can be tracked by both machine builder and user. Coupled model provides better transparency of machines that can be used for product quality inspection, lifecycle management and design improvement. Data accumulated for machines of a same type can be further used for machine-to-machine comparison and data mining tasks.

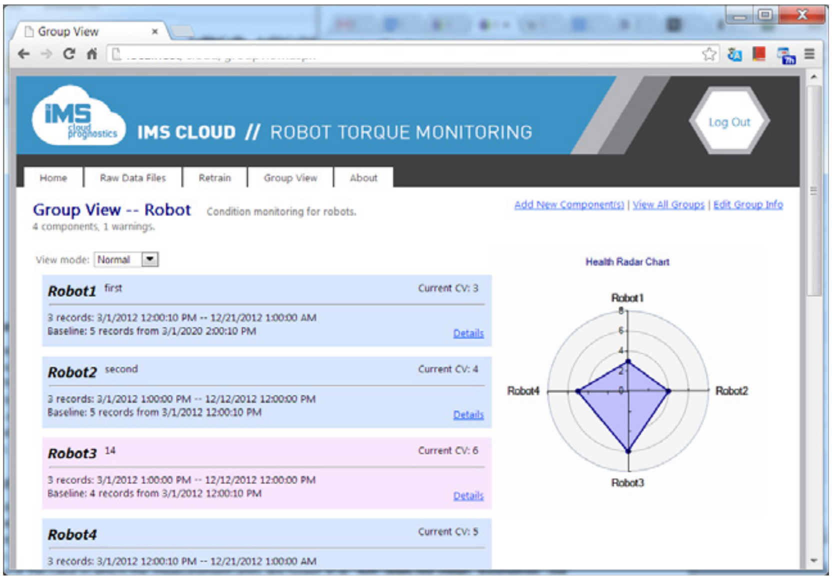

Figure 4: Web interface for visualization of PHM results in cloud based PHM servers

5. Conclusion

PHM systems for manufacturing industry have not been widely implemented despite the extensive research on PHM in academia, which is mostly due to high costs in both development and implementation of PHM solutions in industrial applications. In this paper we try to tackle this issue by adapting cloud computing paradigm with PHM systems to provide high readiness, easy-to-configure, low cost and on-demand PHM services. The cloud based PHM system utilizes the *Infrastructure as a Service* model provided by cloud computing, provisions individual virtual machines as pre-configured PHM servers for each industrial user and formulates PHM solutions as workflows defined by PHM workflow configuration files. Besides the easy-to-use features, the cloud based PHM system also offers easy ways to share PHM solutions among users and opportunities for advanced data mining and knowledge discovery & accumulation tasks.

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