Prognostic Health Management System for Cryocooling Systems

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ABSTRACT

Various high performance sensors and superconducting devices are playing an increasingly important role in medical, scientific, industrial, and US government applications particularly in DoD related activities. For these devices to operate properly they must be cooled to very low (cryogenic) temperatures. A healthy and reliable mechanical refrigeration system (cryocooler) is critical for reliable performance of these sensors. The ability to accurately predict the "health" or remaining useful life of the cryocooler has significant benefits from the viewpoint of insuring and meeting the mission objectives with a high probability of success. The proposed paper provides an overview and approaches used for the development of a Cryocooler Prognostic Health Management System capable of assessing the cryocooler "health" from the viewpoint of the level of performance degradation and/or the potential for near-term failure. Additionally, it quantifies the reliable remaining useful life of the cryocooler. While the proposed system is focused on the specific application to linear drive cryocoolers, especially for DoD, many of the attributes of the system can be applied to other specialized system hardware in both commercial and U.S. Government agency for situations where it is critical that all aspects of the hardware "health" and "remaining useful life" be fully understood. Several benefits of the health monitoring system are described in the paper.

INTRODUCTION

Aircraft flight health monitoring systems have resulted in benefits related to mission management, mission success, logistics issues, cost savings, inventory management, maintenance and repair schedules, efficiency, reliability of the systems and missions, etc. The cost benefit analysis shown in reference[1] has demonstrated significant need for the health monitoring systems in Autonomic Logistics (AL) of the US Department of Defense. It is clearly understood and widely known that diagnostic and control systems are critical components of autonomic health monitoring systems. Knowledge of the diagnosis and prognosis of any engineering system enables a better management of resources and time and allows better control of the mission risks, ensured reliability and AL support as described by Hess et al.[2] In essence a robust and integrated prognostic health management (PHM) system is essential and critical for the AL. As a result of the overriding benefits and advancements in computers, information systems, sensors, electronics, wireless communications, avionics etc. technology has provided impetus and aided the development of powerful health monitoring systems.

Success of critical DoD missions is dominated by a family of high performance sensors which operate with improved and very reliable performance and sensitivities if cooled to very low (cryo-

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genic) temperatures (for example various IR sensors), or only operate at these low temperatures (for example those incorporating the effects available due to superconductivity). A mechanical refrigeration system (cryocooler) is required to cool and maintain the sensor package to cryogenic operating temperatures within a specified range during the mission, and safely return the sensor package to ambient conditions at the end of mission.[3,4] All of these functions must be carried out successfully over a very wide range of ambient temperature conditions along with the associated vibration, ("g" levels) and electrical input power constraints of the mission platform (aircraft).

It is obvious that the diagnostic parameter measured by the sensors at system and component levels provides information about the general health of the cryocooler but it is not enough to derive and make intelligent and cost effective decisions. However, the value of these parameters is greatly enhanced if the parameters could be translated to the root cause level and pinpoint the exact location or part of the system and quantify its remaining useful life, probability of failure, and urgency of the situation in order to assure a safe mission. Uncertainties in the design variables and degradation mechanisms that govern the performance and reliability (such as fabrication, material, load, operation, component and/or system interface, human factors, etc.) of the component and cryocooler system makes it difficult to quantify the remaining life with desired confidence. Therefore, it is essential to consider these uncertainties in the remaining reliable useful life (RRUL) quantification/prediction. Reliability based algorithms along with the historical and real time data needs to be integrated in the prognostic health monitoring system to predict the RRUL.

The present paper outlines and describes the development of a generic, full-scale, in-flight real time Cryocooler Prognostic Health Management System (CPHMS) software tool based on the physics of degradation modes, failure and actual failure data (past experience, ground tests) and reliability models/algorithms. The predictive prognostic models utilize expert knowledge to identify possible failure mechanisms, including past performance and test data, degradation modes, and effects of uncertainties in the involved variables. CPHMS under development allows the identification of questionable cryocooler operating characteristics in a logical physics-based manner based on a detailed understanding of the various failure modes or performance degradation mechanisms present in the cryocooler. This will allow an informed decision to be made on whether to replace the cryocooler module or perform the mission with the current or repaired hardware. The software tool under development is generic, user friendly, applicable to different class of cryocoolers and intended for easy interface with other tools of the Autonomic Logistic System.

CRYOCOOLER PROGNOSTIC HEALTH MANAGEMENT SYSTEM (CPHMS) CONCEPT

The outlined CPHMS concept is based on its capacity of assessing the cryocooler "health" to determine the level of performance degradation and/or the potential for near term failure. It utilizes the data accumulated during actual missions, past performance test data of other similar cryocoolers and an adaptable ground based test cart which can carry out specific diagnostic tests at a level of sophistication and detail which is not possible during actual mission. Through the use of specialized test sequences, data collection via readily installed (and removed) test sensors, existing cryocooler system sensor or controller parameters, and the use of cryocooler simulation models, the described integrated CPHMS package allows all of the critical cryocooler parameters to be identified. Also, the evaluation system allows identification of questionable cryocooler operating characteristics in a logical physics-based manner based on a detailed understanding of the various failure modes or performance degradation mechanisms present in the cryocooler.

Additionally, the concepts of modeling uncertainties and performing the probabilistic and reliability analyses are incorporated in the CPHMS to quantify the reliable remaining useful life (RRUL) of the cryocooler components and/or system in real time and use on aircraft systems under different hardware, software and communication platforms. The benefits of insuring mission critical functions with a very high probability of success with the ability to reliably and accurately predict the "health" or reliable remaining useful life of the cryocooler will be described. Modeling of uncertainties involves identifying the variables critical to the performance and reliability and quantifies their sensitivities on RRUL. Important steps and technical approach used related to Cryocooler Prognostic Health Management System (CPHMS) model and tool development are: (i) Identify reference or primary cryocooler configurations, their components, subsystems and system, (ii) Define and identify critical failure modes and controlling variables and related uncertainties at component and system level, (iii) Develop life prediction and degradation models for components, subsystems and the system, (iv) Develop physics-based prognostic models defining the operating characteristics and cryocooler health/conditions, (v) Develop and apply reliability-based tools to compute RRUL, (vi) Develop a database of the available test data and verify/validate the CPHMS, (vii) Implement and integrate the above in a user friendly object-oriented CPHMS software tool.

Specific important aspects of the above steps such as reference cryocooler, diagnostic/prognostic process/models, data integrations and synthesis, reliability based approach and CPHMS integration process are described in the following sections. Although the CPHMS development is complex with varied demand, its development is generic, object-oriented and modular in order to make it flexible and powerful enough to accommodate easy expansion, modification, installation and execution in order to cater to the need of adding other existing and new classes of cryocoolers.

Reference cryocooler

Although the fundamental CPHMS infrastructure concept is applicable to varied cooler configurations, the focus of the current effort is on small, single stage, free piston linear drive devices, employing the Stirling or Pulse tube cycle of the "tactical" type. The main purpose of focusing on the Stirling class of cooler is to demonstrate the capabilities of the CPHMS with the available test data. Also, the latter distinction is important since a number of the degradation or failure mechanisms to be evaluated and implemented in the present development are unique to these classes of coolers. For example wearing components (contacting seals and bearings) are generally applied in these designs due to the limited life requirements that are not applicable to long life designs that would need to employ non-contacting components (gas or flexure bearings). The use of the latter components would place more emphasis on degradation and failure mechanisms such as contamination, intermittent seal contact and debris generation, or long-term linear drive system component changes.

Figure 1 depicts a schematic representation of the reference cryocooler employed in the current CPHMS effort.[5,6] The unit provides in excess of 1 watt of cooling at a temperature of 75 K in a high ambient condition and utilizes a Stirling cycle. An opposed piston linear drive compressor provides input power to the refrigeration cycle. The expander assembly is coupled to the compressor via a transfer tube. The expander itself contains the moving displacer and regenerator assembly, mechanical springs, and the cold finger assembly. The sensor is mounted to the cold tip of the latter and surrounded by a highly efficient insulation package. As noted in Figure 1, the electrical power to drive the linear motors is provided by a power conditioner and controller which receives its power from the system platform. The entire cooler system is mounted to a cold plate that acts as the final heat sink. In the application under investigation this cold plate is maintained to a specific range of temperatures. A number of thermal paths exist between this cold plate and the linear compressor and expander assembly all of which are critical to overall cooler operation. Each individual cryocooler system is part of a larger cryocooler "array" (6 or more coolers) which operates in an

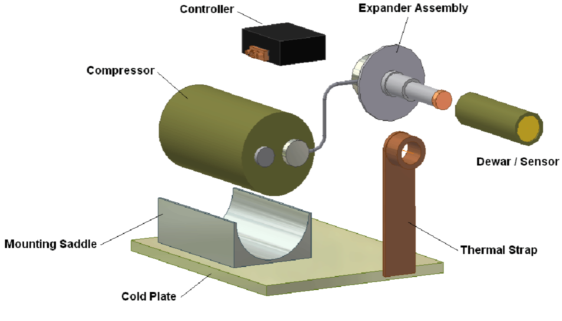

Figure 1. Reference cryocooler configuration and key components.

integrated manner. Under these conditions all of the coolers must be functional. A very important criteria is that they all be able to cool down to the desired operating temperature in a short time period since the integrated system will not function to its full capability until this occurs. A key issue in the implementation of a successful CPHMS is the availability of "data" concerning the operating parameters of cooler. The advent of microprocessor based power conditioners and controllers[7] provides a dramatic improvement in this area.

PROGNOSTIC AND DIAGNOSTIC MODULE

The prognostic and diagnostic (P&D) module acts as the "front end" of the overall CPHMS. Its primary function is to monitor the operation of the cryocooler system in an effort to identify any distinguishing signs or characteristics (diagnostic process) that would indicate that the system is operating outside of the range expected. During this phase the P&D module has access to the overall database and historical data for all cryocoolers of this type. The generated data is compared with the reference values. The diagnostic part of the module identifies if the cooler is outside the operating environment for the P&D module, shown schematically in Figure 2, in which the performance attributes of a cryocooler system are noted as a function of operating time or a related parameter. The prognostic elements of the module become active and work in conjunction with the diagnostic elements to start the prognosis definition process. The diagnostic module provides a clear indication of the likely components of the system experiencing the degradation. Figure 2 depicts a performance parameter below which the cryocooler is considered to have failed, in the sense that it can no longer meet the minimum system requirement.

The basic approach employed by the P&D module is working at four levels during the evaluation process. Figure 3 shows the last two levels of evaluation schematically. The process of identifying the likely root cause of the degradation is iterative in nature and dependent on a detailed understanding of the basic free piston linear drive cryocooler physical and nominal operating characteristics, which are readily available from the vendor hardware specifications and would represent the unique cryocooler input into the generic P&D module sub models. At the onset of the degradation process, the P&D module will utilize an "expert" system to make an initial "best" guess at the degradation process. The initial guess is based on a comparison of the operating data with the reference data and on the sensitivity studies performed using the possible degradation modes and its impact on the unit life. At the next level of evaluation process, the point at which the system has left the normal operating regime and entered into the degrading phase is identified. At the next level of evaluation, data synthesis is performed to provide: (i) degradation attributes, (ii) parameters deviating from the normal values, (iii) deg-

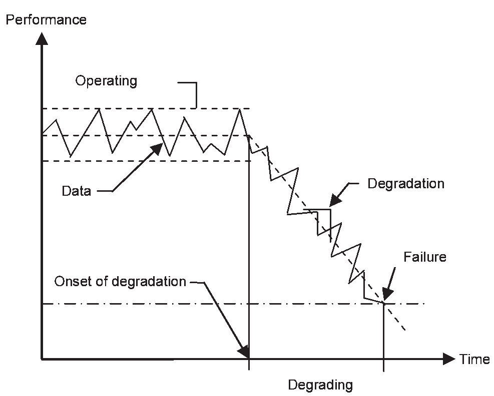

Figure 2. Cryocooler system operating regions.

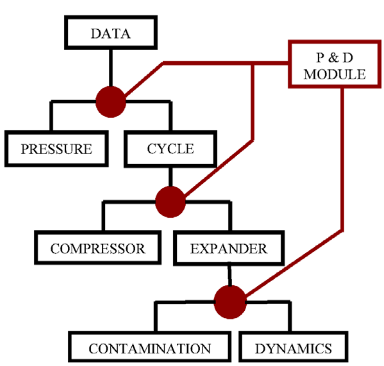

Figure 3. P & D module evaluation process

radation model assessment, (iv) specific diagnostic tests, and (v) processing the data. Once this degradation mode is selected, the P&D module will define the current and projected future characteristics of the cooler. If the cooler continues along the track expected, the P&D module will continue to provide information to other portions of the CPHMS which will estimate RRUL in the last level of evaluation. If the changes in the cooler do not track with the initially selected degradation process, the P&D module will make a new best estimate using the current degradation mode derived from the available real time parameters, based on all of the data available to date, which would also include results of routine but specialized diagnostic testing and probabilistic and maximum likelihood theory. Due to the unique operating characteristics of the free piston linear drive system, the confidence in making the "right" degradation mode decision grows quickly with time.

With the above described information from the P&D module is available, the prognostic and diagnostic elements, working in conjunction with the remainder of the CPHMS, will be able to make an initial forecast or prediction of the RRUL of the cryocooler. As cooler operating time increases the P&D processes continue, thus providing a real time best estimate of the RRUL.

Data availability and synthesis

As previously noted, if sufficient data on specific operating characteristics of a free piston linear drive cryocooler are available and selective "off design" tests are performed; it is a relatively straightforward process to identify the root cause of the degradation being experienced. In reality, it is highly unlikely that this level of instrumentation will be available even in extremely high performance systems. This is due to the complexity, cost, and lack of inherent reliability of many of the required instruments that in total, yields an unacceptable overall system. For the current reference "tactical" cryocooler system, the available sensor data are extremely small.

The primary approach to acquiring the necessary data for successful operation of the P&D module will be to first utilize all currently available data (information), attempt to expand this information via the data synthesis process, and finally if necessary add an absolute minimum of "new" features to the existing cryocooler system. These "new" sensor related items would be external to the cooler itself and in many cases employ a simple MEMS based sensor element and most importantly some type of memory / data storage feature. To overcome these issues, the current P&D module will first utilize all currently available data from the CPHMS database that is continuously updated via information from all similar cryocoolers in use. This database provides generic parametric data, which can be used, with input from other CPHMS modules to help in the definition of the critical transition from a "healthy" to a degrading condition. The information is further expanded collectively via a unique data synthesis that is integral to the P&D module and applied to the specific cooler being monitored. This data synthesis process employs a number of techniques with a heavy emphasis on exploiting the unique operating characteristics of the free piston linear drive system. The latter allows the P&D evaluation to focus on only "real" operating conditions since the free piston linear drive system will only function properly over a very narrow range of parameters. In addition, the fundamental response of this system to various forms of degradation can be used in the process of defining the root cause. As an additional aspect of the P&D module development effort, the various risk / benefit trade-offs concerning adding additional sensors will be investigated. These "new" sensor related items would be external to the cooler itself and most importantly have a memory / data storage feature but not impact the operation of the cooler itself.[7]

Reliability based aspects of the CPHMS

The important uncertainties involved in the design and operation of cryocoolers are those related to the mechanical (structural), electrical, electromagnetic, electronics, thermal and controller disciplines. Possible root causes of uncertainties are variations in the material processing, manufacturing, fabrication and assembly process, mission loads, extreme environmental conditions, operation conditions, boundary conditions and interfaces, etc. Random occurrence of these uncertainties results in their unexpected performance degradation or premature failures. Real time health monitoring of the cryocoolers enables one to quantify the effect of these uncertainties and allows one to make reliable and low risk or risk free mission decisions using the appropriate test validated prognostic models that account for such uncertainties during the operation of cryocoolers.

Predicting RRUL of cryocoolers requires the knowledge obtained from test data, analytical approaches, from the physics involved and from appropriate uncertainty modeling in the time domain. A reliability-based system level prognostic model that represents the cryocooler requires a synthesis of various uncertainty analysis methods. The technical approach adopted in the reliability-based CPHMS development and analysis relies largely upon the nature and the source of uncertainties, the involved disciplines, the behavior of individual components and the interaction among them and the governing physics.

The quantification of the RRUL of the cryocooler involves: (i) analytical quantification of the remaining life of the component and system using test-verified prognostic health models, and (ii) the current state of the system using diagnostic parameters. Major steps used to quantify the reliability-based RRUL are: (i) identify and quantify the design and operating variable uncertainties at component and system level, (ii) augment physics-based diagnostic/prognostic performance models with uncertainties, (iii) collect the current state and recent data from the operating cryocooler and update uncertainties using a Bayesian approach[8,9], (iv) apply time domain based reliability algorithms and quantify RRUL, (v) identify the governing variable sensitivity, (vi) identify the root cause of the degradation/failure and develop guidelines for maintenance, repair and retirement of the components or system in order to reduce or eliminate the risk.

A transient probabilistic analysis that couples different components and their disciplines is followed as a part of the overall approach. A stochastic process-based approach (function of time such as loads, material behavior, degrading parts, strength, performance, efficiency, etc.) that integrates uncertainties to simulate the long-term behavior is used. The reliability based approach models the failure or a relationship between the actual state and the limiting capacity. A cryocooler component or system is considered failed when it can not deliver a minimum desired level of performance, such as a cool down time above a certain value which is not acceptable for the sensor to perform adequately or a component or system actually breaks (hard failure). For example, a component failure occurs when an actual state/condition/stress (*S*) or a load effect exceeds a strength/resistance limit (*R*). The probability of failure is defined as, $P_f = P(R-S \leq 0)$ and is mathematically expressed as:

$$P_f = \int_{-\infty}^{\infty} F_R(x) f_S(x) dx \tag{1}$$

where reliability = 1 - P_f. It is assumed in the above equation that the load effect and resistance are statistically independent.

$$P_f = \int_{\Omega \varepsilon X} \cdots \int f_x(X) dx \tag{2}$$

If E_i denotes a failure mode in a component, then the failure event of a series system is given by: $E_f = E_1 \, U \, E_2 \, U \, ... \, U \, E_n$ and the failure probability is given by $P_f = P(E_f)$. If each failure mode E_i is defined by a limit state g(X) = 0, then the failure probability is an integration of design variable X in failure domain Ω.

In order to capture the actual level uncertainties in the predictions, it is best to update the uncertainties using the actual operating data and enhance the confidence and reliability of predictions. The Bayesian approach[8,9] that accounts for multiple variable cross correlations is integrated with the time domain reliability based analysis. The Bayesian approach involves three major steps: (i) Use maximum likelihood estimates to develop likelihood function based on the observed data, (ii) Combine the likelihood function with the prior distribution to quantify posterior distribution, and (iii) Perform model validation using goodness-of-fit tests or other statistical methods depending upon the nature of data and uncertainties. The Bayesian approach uses condition-based logic (shown in the equation below) – and can be read as - *given this information then I expect these results*.

$$f(\theta \mid DATA) = \frac{L(DATA \mid \theta) f(\theta)}{\int L(DATA \mid \theta) f(\theta) \, d\theta} \tag{3}$$

where *f(q)* is the probability distribution function of the variable *q* and *L(DATA)* represents the likelihood for the available *DATA*.

CPHMS integration

The current CPHMS has five major modules: (i) Executive Module, (ii) Data Acquisition System, (iii) Database System, (iv) Prognostic Analysis Module and (v) Communication & Reporting Module. The Executive module controls operation of the entire software system and enables the decision making process. The Data Acquisition system collects data from the cryocooler sensors of individual coolers on the aircraft and those from other coolers on other aircraft. The Database System maintains and organizes data collected for further processing and characterization. The Prognostic Analysis Module performs prognostic analysis and quantifies the RRUL. The Communication and Reporting Module is responsible for communication between aircraft and ground and other aircraft and reports the results of prognostic analysis. A detailed CPHMS flow chart is given in Figure 4.

The overall CPHMS system consists of each individual Aircraft CPHMS (AC-CPHMS), connected to AL, managed and controlled by the AL Executive Module. The data from the AC-CPHMS are stored in the AL database management system and shared with other AC-CPHMS of the fleet. Thus each AC-CPHMS benefits from the information, data and experience of other AC-CPHMS creating a large number of samples for the reliability-based physics-based prognostic health management system to characterize/update uncertainties using the Bayesian approach. Revised degradation and failure models are used together with the physics-based performance, efficiency and life models to quantify the component reliability, system RRUL and sensitivity of variables. This allows sound cost effective decisions with assured safety and success of missions. Each AC-CPHMS has access to the inventory and supplier chain management system and other parts of the AL System in order to assist AL in making decisions for inspection, maintenance, repair, and replacement or retirement so as to reduce the down time.

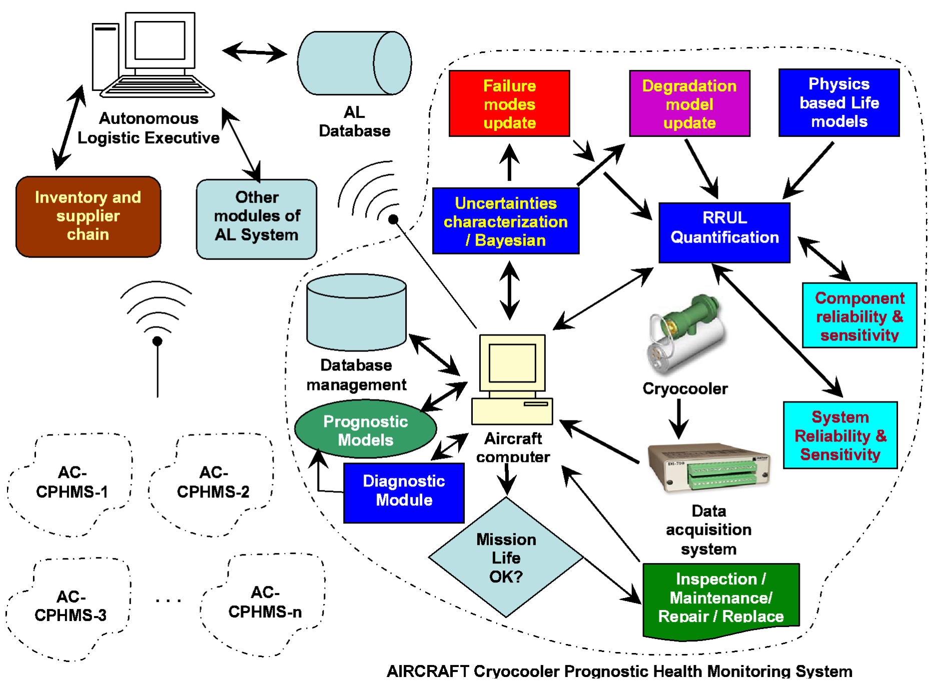

Figure 4. Cryocooler Prognostic Health Management System

AC-CPHMS continuously runs and evaluates the RRUL and provide prognosis and diagnosis of the system to the aircraft pilot and ground area manager. The samples of actual data from other aircraft(s) CPHMS are also collected from the AL System and stored in the AC-CPHMS when the aircraft is on the ground as well as during mission through wireless communications.

Software development

In order to achieve the objectives, the state-of-the-art software development process using object-oriented programming[10] is planned for CPHMS development. Object-oriented (OO) programming focuses not on the instructions and operations a program uses to manipulate data, but on the data itself. First, the program simulates or models objects (cryocooler) in the physical world as closely as possible. The objects interact with each other to produce the desired result. For example, health monitoring is an action and cryocooler is an object upon which several actions can be applied. More than one object can be created with several object (cryocoolers) types having its own characteristics such as components, subsystems, operational, functional, etc. identifying themselves uniquely. Associated with the object are actions which are closely related and interface with the associated data of an object. The data is said to be *encapsulated* because the only way to access it is through one of these surrounding actions. Actions in the case of a cryocooler could be degradation, life and reliability assessment, etc. The encapsulated internal characteristics of an object are its *variables*. Variables are associated with an object and exist for the lifetime of that object. Thus, OO programming allows CPHMS applicable to any type of cryocooler with modularized modifications.

SUMMARY

A Cryocooler Prognostic Health Management System to predict the reliable remaining useful life (RRUL) at any time during the operation of cryocooler has been described. The outlined CPHMS is capable of assessing the cryocooler "health" to determine the level of performance degradation and/or the potential for near term failure. Diagnostic and prognostic models and a reliability based approach using the data accumulated during actual missions (using installed sensors and controllers), past performance test data of other similar cryocoolers and adaptable ground based-tests forms the core of the CPHMS. Simulation models provide sensitivity of governing variables and identify the degrading or failing components and point to the root cause of the problems. It enables developing maintenance, repair and replacement/retirement schedules and guidelines in order to control parts inventory. The described CPHMS software tool uses the objected oriented (OO) programming technique in order to make it generic and applicable to a large class of cryocoolers. OO programming makes CPHMS user friendly and easy to expand, enhance, modify and easy to integrate with different hardware platforms and communication protocols. CPHMS under development not only assures the reliability and success of the mission but also mitigate and/or eliminate associated risks.

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