Integrated Health Management and Adaptive Control Systems

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Abstract: Described is an integrated health management and adaptive control system that has a hierarchical structure whereby the overall authority is allocated to a “performance management system” (PMS). All dynamic systems require some form of monitoring and health management system (HMS). There are numerous HMS codes that present a partial approach to system status monitoring and diagnosis, in the sense that a system either has a failure or not. There are no algorithms available that treat the complete picture of system performance evaluation integrated with an HMS at every time step to make sure that all commands are being implemented the way they should and that the system performance is nominal. An integrated system is proposed herein that requires, as a minimum, a sensor-data-validation-system that can eliminate failed sensors and switch to redundant ones when possible. If there are not enough redundant sensors then it is necessary to create some form of analytical redundancy. The next step is to have a good monitoring system both for fault detection, isolation/identification and for performance. So once the sensor data validation system clears all sensors of any faults the PMS takes over and tries to determine if the engine performance is within acceptable limits. If not, then either there is a fault or the control system needs some adaptation. The HMS will determine any fault that effects performance measurements. The PMS, on the other hand, with some sophisticated logic, will try to determine the cause for the off-nominal performance and adjust the control commands in an adaptive way so as to lead the system to nominal operation.

Introduction: Demand for advancements in control and HMS with enhanced performance, high reliability and durability and ease of maintainability is getting ever greater. Control systems can be enhanced by improvements in component performance and reliability/maintainability, or by the introduction of advanced intelligent and adaptive systems with highly reliable fault detection, diagnostics, isolation and accommodation capabilities. Fault detection, identification, diagnosis and accommodation (FIDA) can be achieved with pure signal based, or a combination of model-based and signal based approaches. The former is performed via logical/intelligent use of measurement data in appropriate algorithms. FIDA can also be accomplished by the latter approach when the fault is performance related and not purely structural in nature, by utilizing good analytical models that well-reproduce the performance characteristics of the critical signals of the system at hand. This is done by comparing the model predictions with the actual measurement output and the intelligent/logical processing of the residuals between the two, with a proper algorithm [1]. One of the fundamental advantages of model-based techniques is that, it can be set up such that the model, running with the same inputs/commands as the actual engine, will only predict the nominal outputs. While the engine closed-loop system will continuously update the commands to accommodate any anomalous behavior, such as leaks, based on measurement feedback. Thus, any change in performance that is caused by closed-loop compensation will, in general, be detectable with model-based approaches [2-3].

All FIDA schemes are based on the assumption that anomalies effect the critical parameters of a system and produce a definite discriminating signature. These are the signatures obtained from a diagnostic module that analytically define the specific effects associated with each specific fault. Diagnostic models are derived from the residuals between the measured and predicted values of the corresponding parameters, in such a way that the signature direction points to a known fault [4]. The measured parameters can be considered as the dependent variables, in which the amplitude of change determines the levels of change in the primary performance parameters. Hence, if physical performance degradation results in change in a component’s characteristics, which is exhibited in the engine measurements, then it is possible to isolate the faulty component based on the measurable changes. This approach is taken when a system correlation/sensitivity matrix is developed via “influence coefficients”. The latter essentially describes the Jacobian of the non-linear system, which is a relation matrix of the dependent with respect to the independent parameters, and is used to correlate measured changes with unmeasured/predicted (computed with a model) performance degradation [5-6].

There are cases when system performance is off nominal and yet without it being the result of a fault. This type of behavior occurs when the controller commands do not produce the required response either due to some form of system mis-calibration or improper controller feedback gains or some other unknown reasons. In such circumstances, if not careful, a HMS will identify such off nominal performance as anomalous and recommend actions, which could lead to even further performance deterioration and failure. To eliminate such system misdiagnosis it is prudent to have a performance management system (PMS) that oversees system performance at every time step and ensures nominal performance.

In all FIDA and PMS techniques the success of the algorithms depend on the degree of accurate predictions of both nominal and faulty conditions of the system. For, the models of the faulty processes define known effects associated with specific faults. If it is believed that the faulty process models distinguish different faults then the residuals carry the whole weight of meaningful information regarding the system condition. The accuracy of the algorithm prediction is a direct function of the architecture and details of all the dynamics, of each and every component and part of the system, in the model and the accompanying complexity due to couplings between parameters. There are always tradeoffs between algorithm/model complexity and detail versus ease/tractability of computations [7]. Usually the relevant information is captured in some relational system database with proper functional and operational connectivity. For on-line real-time algorithms the degree of accuracy is usually sacrificed for computational simplicity. The robustness of the algorithms is also related to the model accuracy and the repeatability of performance when under uncertainty and variation. However, modeling errors and sensor and system noise are the main obstacles to accuracy in model-based systems. For, these obstacles work even in the absence of failures and limit the sensitivity of the FIDA system and can only be adjusted by a proper PMS. Faults that have differences between the model predictions and the actual measurement data of less than the noise and model errors can not be detected, in principle. The adverse effects of measurement noise on the performance of any algorithm can be minimized by properly averaging and filtering the signal measurement values. Modeling errors, on the other hand, are more difficult to deal with.

The greater demand for reduced life cycle costs, and enhanced reliability obligates major improvements in control systems, diagnostics and prognostic technologies. Advances in data integrity, compression, fusion and artificial intelligence tools can serve as the missing link towards truly cognitive HMS [8]. Some of the perceived problems with HMS practices involve a high number of false alarms, cost and inadequate sampling of engine parameters. These are mainly due to unreliable feature extraction capability and insufficient failure knowledge for diagnosis of failures with expert systems or artificial intelligence [9].

The basic approaches to fault detection and performance evaluation can be summarized as some form of state and output observers or estimators, parity equations generated by parametric or non-parametric models, identification and parameter estimation methods. Other methods include direct comparison of model predictions with measured data and correlation between measured and independent parameters. Fault diagnosis, on the other hand, is usually carried out by probabilistic and geometric distance methods, artificial intelligence or neural network approaches or fuzzy logic [10], among others.

Integrated Health Management and Adaptive Control System (IHMACS) Overview: A HMS will use any off nominal performance data as anomalous and hence due to a fault, while in reality this might be a misdiagnosis. An integrated health management and adaptive control system will have several features that can eliminate such potential misdiagnoses. Described below are the various components of such a system.

In addition to the HMS, PMS and the controller there are peripheral systems that help in the overall performance. One such important system involves data generation and processing. Sensors produce data that is processed in some manner and sent to the controller, HMS and the PMS. Moreover, the redundancy features and the reliability of all these peripheral systems are of paramount importance to have a dependable and robust IHMACS.

Architecture: A complete integrated health management and adaptive control system will have several hierarchical levels of operation (see Figure 1). The fundamental assumption in every HMS, PMS or control system is that all data received from sensor measurements is valid. This might not always be the case. Thus, every such system should have a reliable sensor data validation scheme that has the capability to detect any soft or hard sensor failures and somehow accommodate them. Once this task is accomplished it is followed by system fault detection. There are many approaches to fault detection that were briefly discussed in the introduction above, including signal-based and model-based and a combination thereof. The detected faults need to be identified and properly isolated to a component or even a sub-component level. Faults can sometimes be accommodated relatively easily, such as a simple switching of a failed sensor to a good one, when sensors have built in redundancy. On the other hand, there are some faults that are hard to accommodate. Some of the actions needed to address faults could be related to maintenance, repair or replacement of parts. Hence, maintenance is an integral part of a good HMS.

As the HMS works to detect any anomalous behavior it reports its findings to the PMS. The latter, in turn, evaluates the performance of every parameter and assesses the controller integrity during every time cycle. In case an off-nominal performance of any kind is detected corrective action is recommended. The implementation of the corrective action, if it is performance related, belongs to the adaptive control system, which adaptively modifies the commands until the system performance is back to nominal. If the action is HMS related then the accommodation module, which has to coordinate its actions with the PMS, is in charge. This completes the loop of an integrated health management and adaptive control system.

PMS: The highest authority within the hierarchy of the IHMACS should be with the PMS, since it is of paramount importance to ensure the best performance of a system at all times. For, a system that operates within acceptable bounds all the time will have less of a chance to develop anomalies and failures. On the other hand, best performance should be well defined in order for a PMS to be able to coordinate its goals with the HMS and the controller. Moreover, performance is also a function of the quality and reliability of each and every component and part of a system. A system that has lenient manufacturing tolerances will result in large variability. To develop a robust control system for a plant with excessive variability can be real problematic. Thus, a really integrated system would require the best possible design, manufacturing, integration and maintenance and should strive for minimal variability.

The main feature of a PMS consist of comparison of commands and response outputs to ensure that the correct response is being delivered for a given command input (see Figure 2). Moreover, every key parameter that is being measured has an expected performance that is considered to be “within the family”. One of the important tasks of the PMS is to establish that all parameters are within the expected bounds at all times. This can sometimes be difficult to characterize, however, there can be found reliable ways to develop such “within family” features. Another aspect of a PMS is to evaluate the response overshoots or undershoots. Thus, for a given input, depending on the gains used and the system response characteristics, sometimes the response overshoots the command and then eventually steadies and meets the command. It is desirable to keep the overshoots within acceptable limits or else the system can go unstable.

HMS: The HMS, in any system has a very crucial task to accomplish. It has to determine the occurrence of every fault reliably and with sufficient accuracy. That is, it should not predict faults when there are none and should be able to predict every real fault in a timely manner to avoid further system malfunctions or damage. In any event, all diagnoses should be transmitted to the PMS for assessment of performance.

The main parts of the HMS entail monitoring, sensor data validation, fault identification and isolation, fault accommodation and maintenance (see Figure 3). Monitoring includes evaluation and checking of sensor data to ensure that they are all valid and correctly measured and the sensors are all healthy, evaluating and checking measured data for anomalous behavior or off nominal performance of any kind, and finally checking for structural faults/anomalies. Isolation deals with sorting out events and correlating them in such a way as to be able to converge on a clearly defined fault scenario that explains what occurred clearly and correctly. Identification, on the other hand, refers to relating a fault to a given component or sub-component with absolute certainty. Once faults are detected and identified possibilities for taking action are evaluated by the accommodation algorithms and logic. The latter will command action to mitigate the fault with proper steps.

Adaptive Control System: For any system, especially aircraft or rocket engines, calibration is performed prior to testing and actual fielding. Sometimes these calibrations are not perfect and, thus the control system responses turn out to be off nominal. To avoid such off nominal performance it is possible to develop adaptive control systems that will automatically compensate for variations that lead to out-of-family performance and adjust the system parameters such that the best possible performance is achieved. For instance, for reasons of simplicity of control systems a single gain is normally allocated to a given controller/actuator for all operating conditions. In reality, however, most control systems do not operate well with a single gain, especially those with nonlinear characteristics. For such systems it would be desirable to have an adaptive means of selecting the right gains for the right operating condition. Furthermore, there are ways to develop adaptive calibration methods that minimize expensive testing and that can adaptively calibrate systems, on-line in a real-time manner.

Conclusions: More and more challenges face the industry related to complexity, cost, autonomy, and robustness. Autonomous and robust systems need all possible information that should be fused in a methodical manner and deep within the process in order to provide the highest degree of performance. The advantages of integrated health management and adaptive control systems have been briefly explained in the above paragraphs. The underlying premise of such a system is the assurance of optimal/best performance at all times in addition to the continuous monitoring and fault detection process that simultaneously provides additional reliability and robustness. This architecture ensures adaptability to numerous systems and increases its usefulness in many applications.

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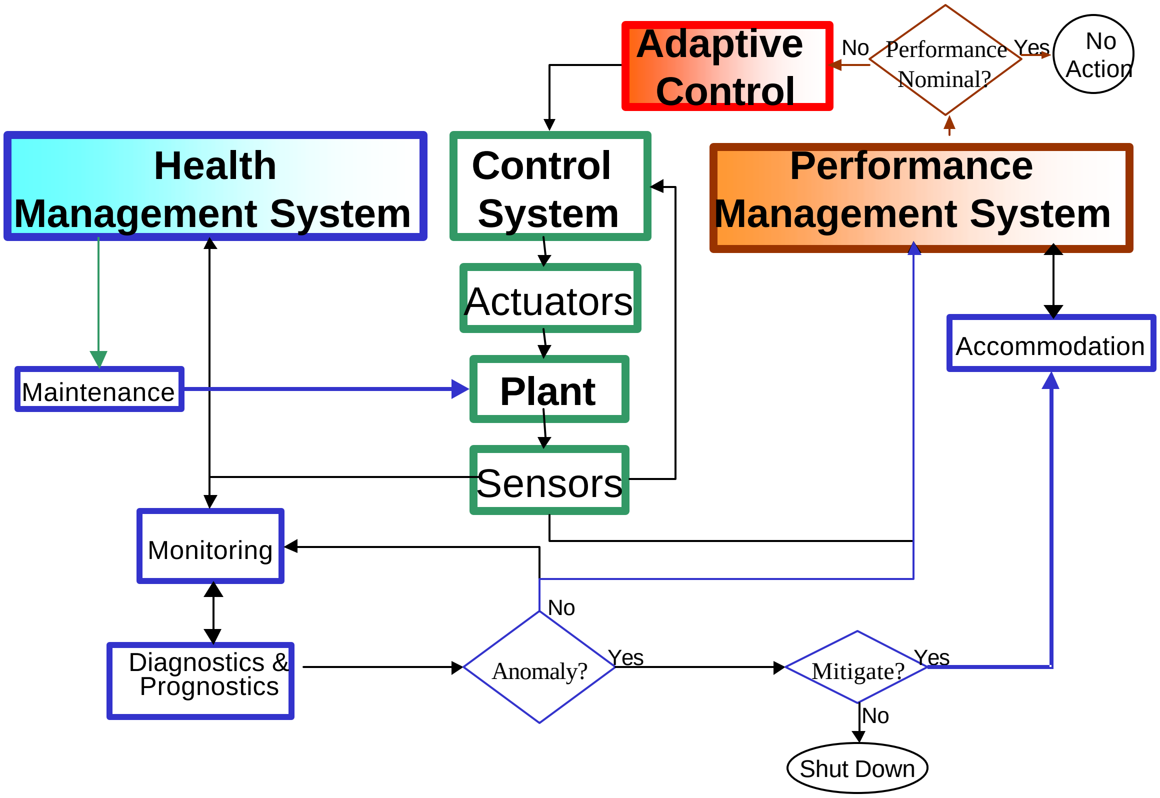

Figure 1. Integrated Health Management and Adaptive Control System Architecture

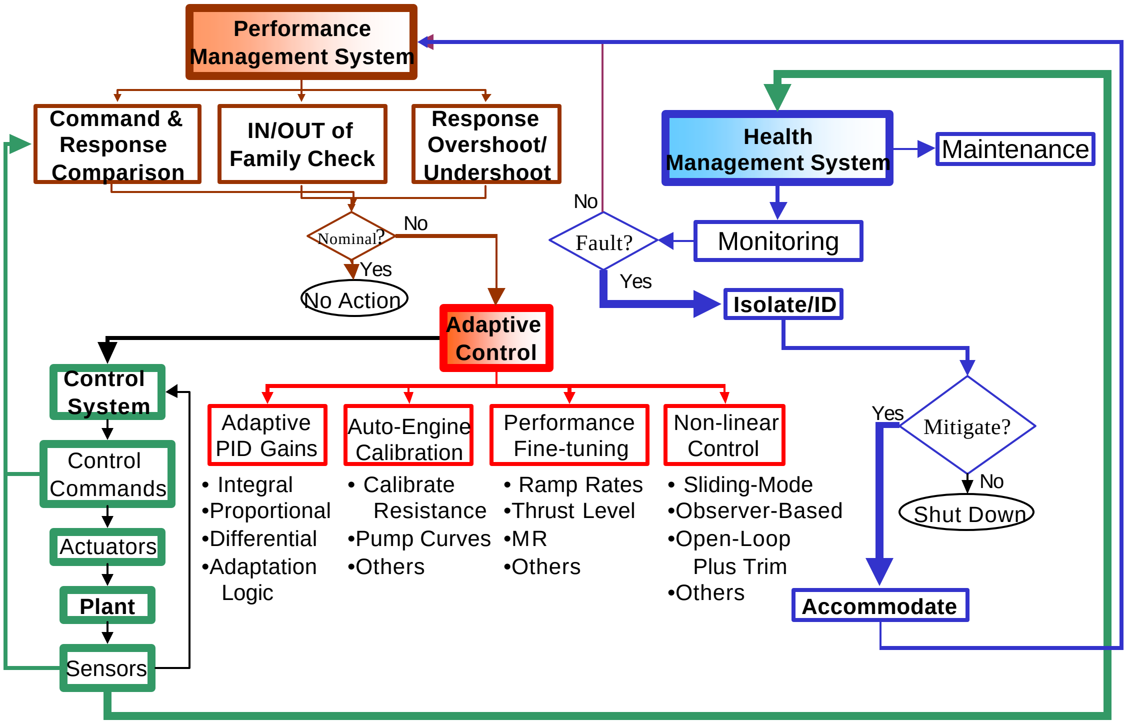

Figure 2 Performance Management System and Adaptive Control Details

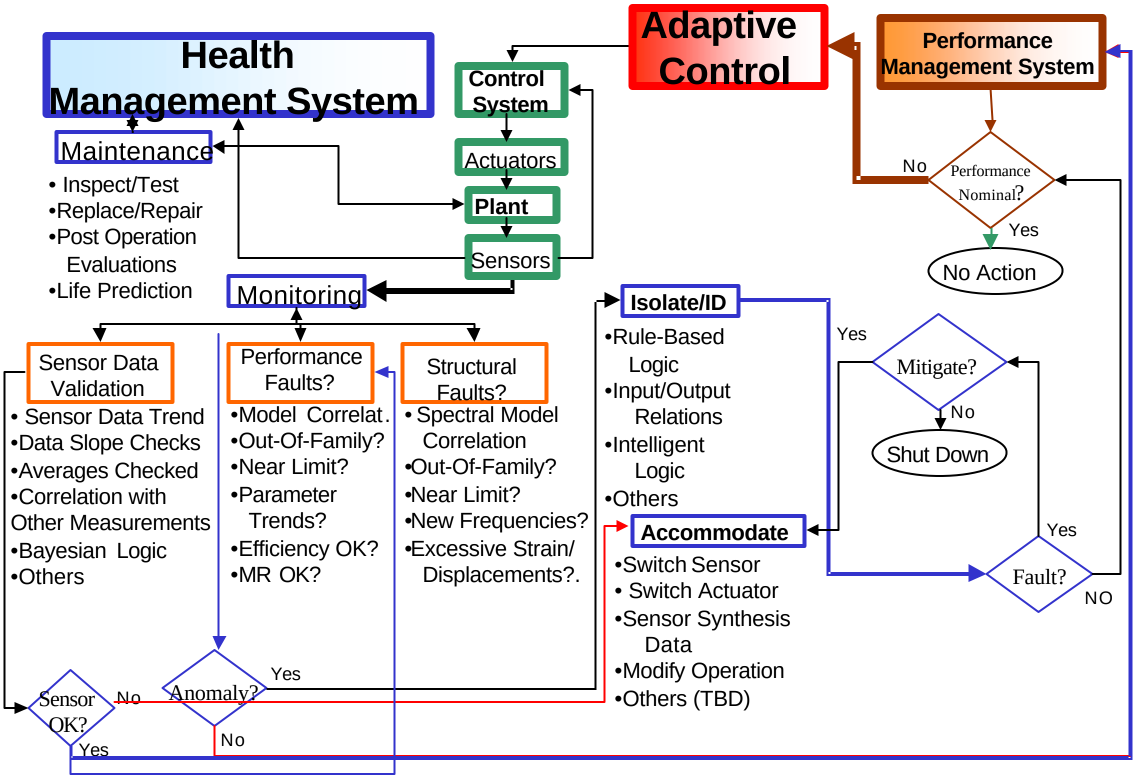

Figure 3. Health Management System Details