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Integrated Vehicle Health Management System: Matlab Simulink

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Abstract

This paper presents an Integrated Vehicle Health Management (IVHM) framework leveraging strategic sensor placement for real-time monitoring of critical parameters such as temperature, pressure, and voltage inside launch vehicles. The system compares continuously collected sensor data against preset limits established by the developers. Upon detecting deviations beyond these limits, the framework initiates alerts or corrective actions to mitigate potential issues. Initially a MATLAB Simulink model was developed, which will later develop into a real time monitoring system using Peripheral Interface Controller (PIC) or FPGA. Launch vehicles may collapse due to environmental changes including temperature, pressure and other climatic variations and causes noise, pollution, financial crisis. Personal health is of utmost importance in missions like Gaganyaan - Human in space. In such cases, the abortion of mission is of high importance for the protection of human life. The IVHM system promotes Launch vehicle reuse and Protection of life in human space missions and thus enhances space sustainability. Less waste and material use, less energy use, less noise, more biodiversity, and of course lower emissions of CO2 and other harmful pollutants are just a few of the immediate advantages, the quality of life, safety, labour efficiency, and the use and consumption of materials are examples of indirect benefits of the IVHM system. The historical data to refine the predetermined limits, is by considering factors like normal parameter ranges, vehicle model specifics, environmental conditions, and driving patterns. This research contributes to the advancement of IVHM strategies and their practical implementation for vehicular health monitoring.

1. Introduction

The Integrated Vehicle Health Management (IVHM [1] [2]) system is integral to the vigilant monitoring, assessment, and lifecycle management of launch vehicles. By integrating sensors, data acquisition systems, and diagnostic algorithms, IVHM enables real-time monitoring, thereby minimizing environmental impact and ensuring long-term efficiency of launch vehicles. In the context of launch vehicles, IVHM is essential for ensuring reliability, safety, and sustainability of launch vehicles [7] and performance across its operational phases. This work focuses on the specific significance of limit checking and dynamic limit checking within the IVHM framework, highlighting its crucial role in securing the safe and reliable operation of launch vehicles. Objectives include anomaly detection, early warning provision, optimization of maintenance strategies, and continuous monitoring of system performance for enhanced safety and reliability. The scope of limit checking within IVHM [1] [2] encompasses fault diagnosis, failure prognostics, data analytics, visualization, continuous improvement, and system health monitoring [4]. As a dynamic and iterative process, it allows for refining limit values based on operational experience and feedback. Emphasizing its critical contribution, the paper underscores the significance of limit checking in safety assurance, reliability enhancement, proactive maintenance facilitation, cost efficiency, and mission success for launch vehicles. The exploration is approached specifically from the perspective of MATLAB Simulink [5]'s limit check capabilities, offering a comprehensive examination of how limit checking in IVHM [1] [2] preserves the health and integrity of critical systems throughout the lifecycle of launch vehicles.

2. Integrated Vehicle Health Management System

2.1 Concept of IVHM

Integrated Vehicle Health Management (IVHM [1] [2]) represents an approach to vehicle maintenance, seamlessly integrating various technologies to monitor and optimize performance continuously. By viewing the vehicle as a cohesive system rather than individual components, IVHM [6] [8] employs data collected from sensors and diagnostic systems, subjecting it to real-time analysis using advanced techniques such as statistical analysis and machine learning to detect potential faults. In the fault diagnosis phase, specialized algorithms compare observed and expected behaviour, aiding in fault isolation and root cause analysis. Complementing this, IVHM [10] [12] incorporates decision support systems that offer well-informed recommendations for maintenance actions, optimizing schedules, and ensuring the vehicle's safe operation. Embracing IVHM [11] [13] allows organizations to transition from reactive to proactive maintenance strategies, minimizing downtime, reducing costs, and maximizing resource utilization through continuous monitoring and timely interventions

3. Limit Checking in IVHM

Limit checking is a foundational concept, particularly crucial in Integrated Vehicle Health Management (IVHM [1] [2]), where its role is paramount for ensuring the safe and efficient operation of systems and equipment. This process involves comparing measured values against predefined thresholds, determining if they fall within acceptable ranges. By establishing limits based on engineering specifications and safety regulations, limit checking enables early anomaly detection, identifying deviations or potential faults promptly. It plays a vital role in performance monitoring and optimization by identifying inefficiencies and ensuring systems operate within desired parameters. Limit checking is crucial for safety assurance, particularly in high-risk environments, helping maintain safety margins and prevent hazardous conditions. As an essential component of preventive maintenance, limit checking enables proactive actions to address potential issues before they escalate, minimizing downtime and reducing the likelihood of unexpected failures. Furthermore, it finds application in process control and quality assurance, ensuring operational processes adhere to specified limits, maintaining stability, and preventing deviations from desired standards.

3.1 Role of Limit Checking

Integrated Vehicle Health Management (IVHM [1] [2]) serves as a foundational element in ensuring the operational integrity, safety, and success of launch vehicles by providing an essential framework for continuous monitoring and analysis. A pivotal aspect of IVHM [1] [2] is its real-time monitoring capability, utilizing data from sensors strategically placed across propulsion systems, avionics, structure, and thermal management. This instantaneous monitoring enables the immediate identification of anomalies or abnormal behaviour, offering vital insights into the health of the launch vehicle [4] during pre-flight, launch, and in-flight operations. IVHM [14] [15] leverages advanced algorithms and data analysis techniques to compare real-time sensor data against predefined limits, enabling the early detection and diagnosis of potential failures or malfunctions. This swift awareness supports timely investigation, root cause analysis, and corrective actions, ultimately mitigating the risks of mission failure and enhancing safety during critical phases.

4. Dynamic Limit Checking

Dynamic limit checking, a process that continually evaluates and adjusts limits based on changing system conditions, is a crucial element in ensuring the stability, safety, and efficiency of various systems, including those in engineering, finance, and manufacturing. Unlike static limit checking, which relies on fixed thresholds, the dynamic approach adapts to real-world scenarios, enabling more responsive decision-making. It plays a pivotal role in autonomous systems, such as vehicles, by continuously assessing dynamic limits related to speed, environmental conditions, and sensor accuracy to prioritize safety. The implementation of dynamic limit checking involves sophisticated algorithms and machine learning techniques, analysing historical data, monitoring current conditions, and utilizing predictive models for dynamically adjusted and informed limits. Challenges include the need for accurate data and real-time processing capabilities, with a constant trade-off between adaptability and stability. As technology advances, refining dynamic limit checking methodologies will enhance the efficiency, safety, and reliability of complex systems. In dynamic limit checks, variables are continuously monitored in real-time, and limits are adaptively adjusted based on current operating conditions, system state, or other factors. The recalibration of limits occurs in real-time to reflect changes in the environment, system dynamics, or user-defined criteria. A feedback mechanism may be in place to provide information on system performance, allowing for adjustments to dynamic limits. Dynamic limit checks find applications in diverse fields such as process control, financial systems, health monitoring [4], and traffic management, where adaptability to variable operating conditions is essential for effective system response. Automation is a key feature, reducing the need for manual intervention and ensuring quick responses to dynamic changes.

5. Diagnostic Method

There are mainly two type of diagnostic methods used. Model based and Non-Model based methods.

5.1 Model Based Techniques

This method is commonly used when the features cannot be measured directly by identification, it relates the physical parameters to fault models. Measures the inputs and outputs of the dynamic blocks and arrives into a conclusion. Model Based Technique Representation are shown in Figure 1.

Motor dynamics,

$$\frac{\omega(S)}{T(S)} = \frac{1}{Js + B}$$

Pump/piston dynamics,

$$\frac{X(S)}{F(S)} = \frac{1}{(M_P s + B_p)s}$$

Actuator system dynamics,

$$\frac{P(S)}{R(S)} = \frac{1}{\left(\frac{A^2}{k}s + L\right)}$$

Therefore, select the physical parameters as the feature vector.

$\phi\ (t)$ = [J B Mp Bp K L] T

Where, J, B, Mp, Bp, K, L are physical parameters.

B - Motor damping coefficient

Bp - Piston damping coefficient

K - Actuator stiffness

L - Leakage coefficient

Model based methods use system identification techniques to estimate the features.

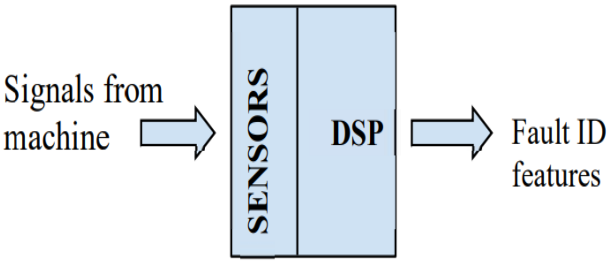

Figure 1 Model Based Technique Representation

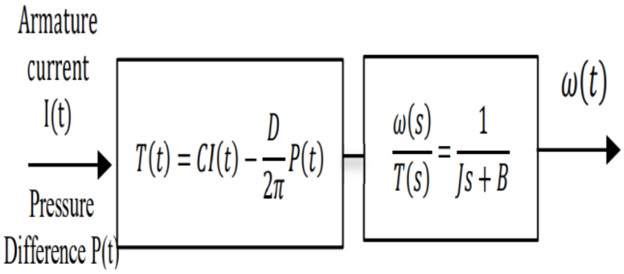

Figure 2 Model Based Technique Representation of Motor Dynamics

5.2 Non-Model Based Techniques

This includes getting expert opinion from manufacturers or from user groups. Get actual fault/failure legacy data from recorded machine histories or run system test bed under induced faults. A rough non model based analysis is given by Table 1, Model Based Technique Representation of Motor Dynamics shown in Figure 2.

Table 1 **An Example of Non-Model based Techniques**

Condition	Fault Mode
IF(base mount vibration energy is large)	THEN (fault is unbalance)
IF(shaft vibration second mode is large) AND (motor vibration RMS value is large)	THEN (fault is gear tooth wear)
Etc.	Etc.

6. Methodology

In the process of Limit checking, upper and lower thresholds are preset for each parameter. Random signals generated are selected one by one using the multiplexer and then compared with the preset threshold. These are done using various blocks in MATLAB Simulink [5]. Flow Chart of Limit Checking in IVHM shown in Figure 3.

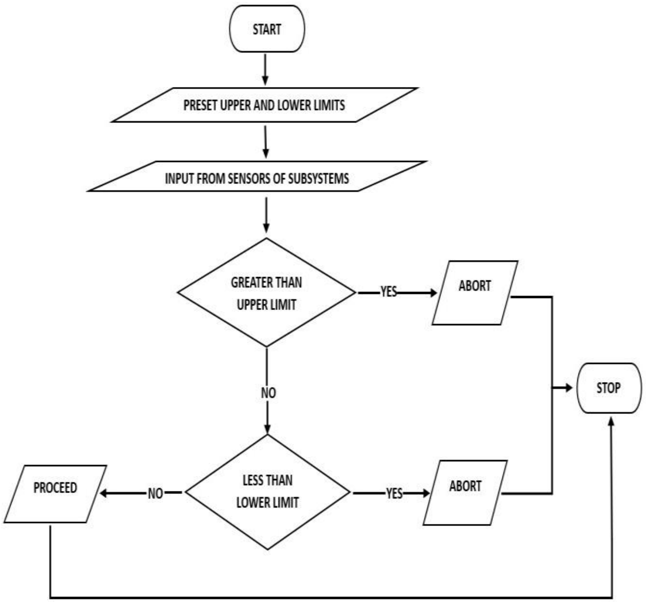

Figure 3 **Flow Chart of Limit Checking in IVHM**

The upper and lower threshold are present and stored in the comparator. The signals from the sensor (Pressure, Temperature, and Vibration) are given to the comparator and checked against the present values. If the sensor output is greater than the upper limit or less than the lower limit, a notification will be given. Else, the process can be continued. Representation of Limit Checking in IVHM shown in Figure 4.

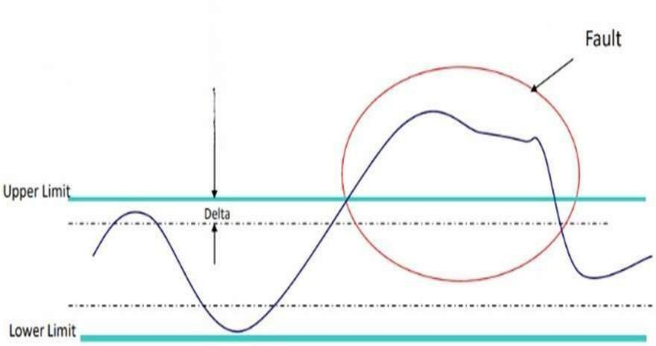

Figure 4 **Representation of Limit Checking in IVHM**

Here, the horizontal lines represent the upper and lower limits, and fault is observed when the input random signal goes above or below the horizontal line. That is when it exceeds the limits, it's marked as a fault. Representation of Dynamic Limit Checking in IVHM shown in Figure 5.

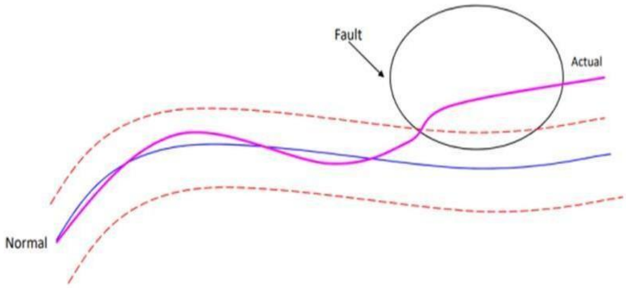

Figure 5 **Representation of Dynamic Limit Checking in IVHM**

Here, the uniform curve at the centre represents the desired signal. Whenever the input signal deviates from the desired signal by a large extent, after checking at every instant of time, the system detects it as a fault.

7. Simulation Setup

7.1 Upper Limit Checking

A random signal was generated and subsequently sampled using a pulse signal. The resulting sampled signal and the pulse signals were then subjected to multiplication through a multiplier. The combined signal was directed to a Multiplexer (MUX) at a designated time, specifically at 0.1 seconds. This configuration represents a time division multiplexing (TDM) system. The output from the MUX was further processed through a switch, which imposed a threshold limit of 0.5. If the signal exceeded this threshold, a binary output of 0 was produced; otherwise, a binary output of 1 was generated. This process effectively implements a decision mechanism based on the amplitude of the signal. Upper Limit Checking in MATLAB

Simulink shown in Figure 6.

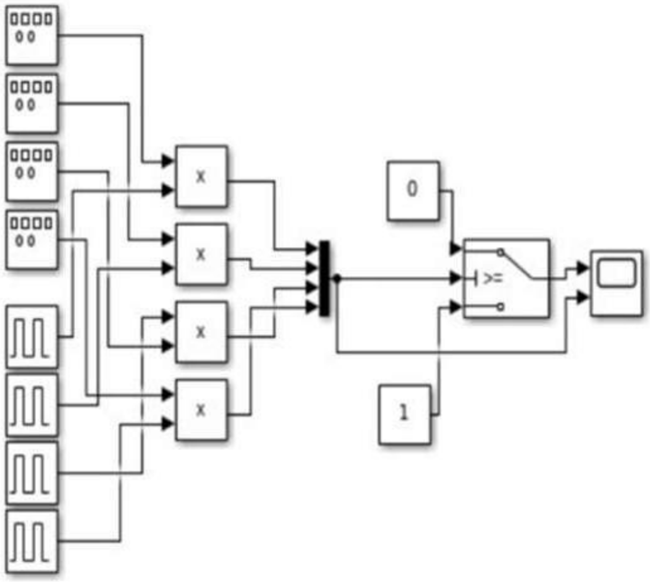

Figure 6 Upper Limit Checking in MATLAB Simulink

7.2 Upper and Lower Limit Checking

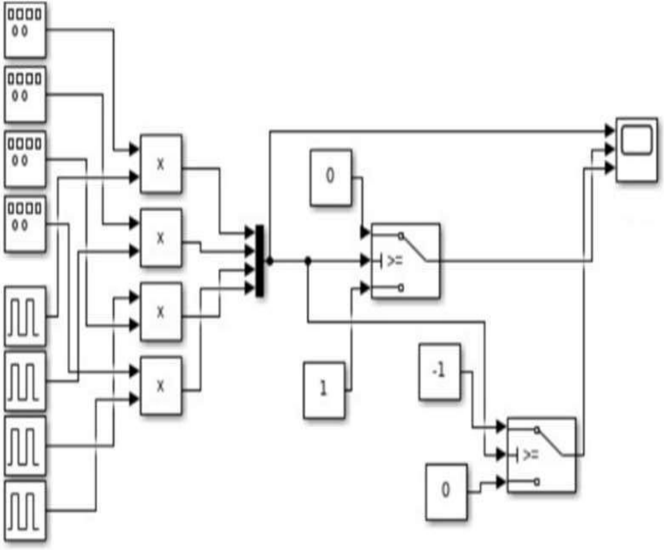

Figure 7 Upper and Lower Limit Checking in MATLAB Simulink

A random signal was generated and subjected to sampling using a pulse signal. The resulting sampled signal was then multiplied with the pulse signal using a multiplier. Subsequently, the combined signal was directed to a Multiplexer (MUX) at a specific time, notably at 0.1 seconds, defining the primary circuit as a form of time division multiplexing. The output from the MUX was further processed through a switch that imposed two threshold limits. If the signal exceeded 0.5, the output was set to 0; conversely, if the signal fell below -0.5, the output was set to 0. For values between -0.5 and 0.5, the output was assigned either 1 or - 1 based on the polarity of the signal. This decision process was implemented to generate the final output. Upper and Lower Limit Checking in MATLAB Simulink shown in Figure 7.

7.3 Dynamic Limit Checking

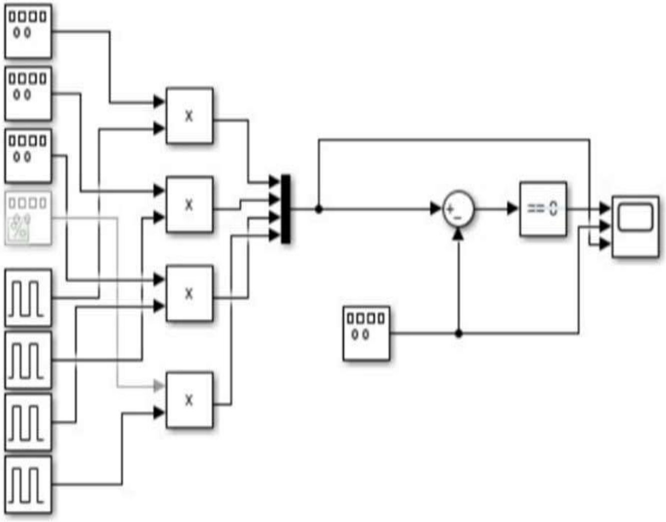

Figure 8 Dynamic Limit Checking in MATLAB Simulink

The random signal which is equivalent to the sensor output which is generated from the signal generator is multiplied with a pulse signal of desired duration (0.01s, 0.02s, 0.03s, and 0.04s). One signal is selected at a time using the multiplexer. A desired signal is given to the “Sum" module, which subtracts the sampled random signal from the desired signal. The points of the random signal having the same value as that of the desired signal will have zero output in the sum module. Zero output points are for which the random signal matches with the desired signal. If the output of the Sum module is zero, a logic high will be shown at the output display for the user to understand that those points of random signal match with the desired signal. Dynamic Limit Checking in MATLAB Simulink are shown in Figure 8.

8. Result and Discussion

8.1 Upper Limit Checking

Output of Upper Limit Checking in MATLAB Simulink are shown in Figure 9.

1. Output signal is shown above and random input signal is below.
2. The upper threshold is set as +0.5 in the comparator (as it’s an approximate average of the input).
3. Whenever the random input goes above the upper threshold +0.5, output shows zero. Else output will be high.

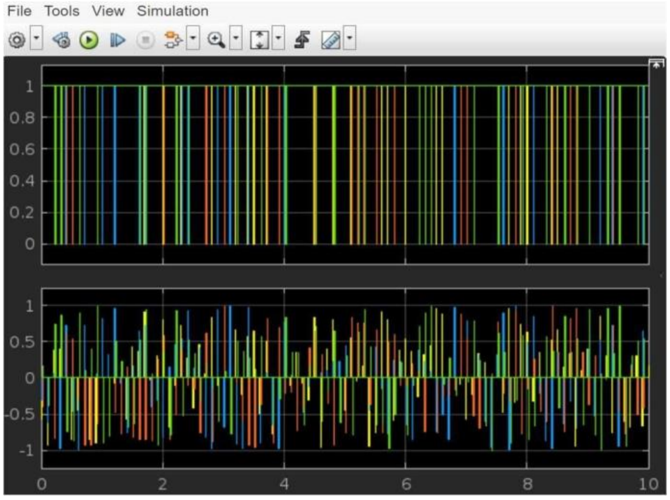

Figure 9 Output of Upper Limit Checking in MATLAB Simulink

8.2 Upper and Lower Limit Checking

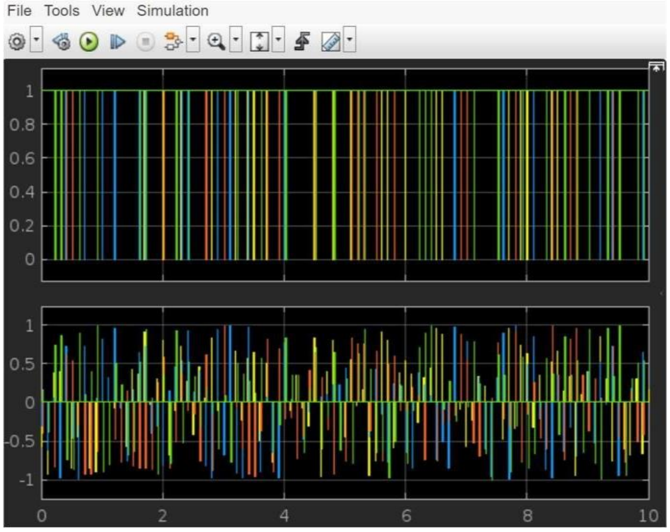

Figure 10 Output of Upper and Lower Limit Checking in MATLAB Simulink

1. Output signal at top and input random signal below.
2. The upper and lower thresholds are set as +0.5 and -0.5 respectively.
3. When the positive peak of the random input goes above +0.5 or negative peak of the random input goes below -0.5, output is shown as zero. Else output is high.

Output of Upper and Lower Limit Checking in MATLAB Simulink are shown in Figure 10.

8.3 Dynamic Limit Checking

1. First signal is the input random signal, second is the desired signal which is given to the sum module, and the third is the output signal.
2. Output is displayed as logic high/1 for the points of the input signal for which its value is the same as that of the corresponding point of the desired signal.
3. Zero output means, on those points input signal value and the desired value are different. This is dynamic limit checking.

Output of Dynamic Limit Checking in MATLAB Simulink are shown in Figure 11.

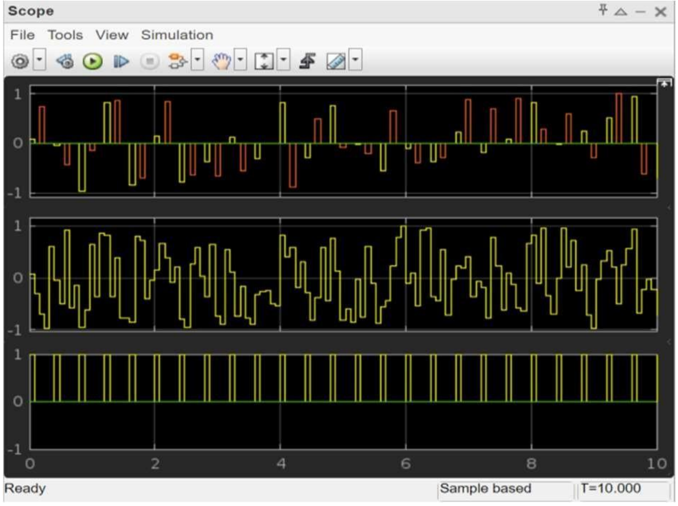

Figure 11 Output of Dynamic Limit Checking in MATLAB Simulink

Conclusion

A four channel IVHM MATLAB Simulink [3] model is done now which can be further converted into a 100- channel real time monitoring system using a PIC microcontroller or FPGA, which is crucial for minimizing environmental impact and ensuring long term efficiency of launch vehicles. By optimizing resource usage, reducing waste, and adopting eco-friendly practices, IVHM contributes to a more sustainable [9] and resilient transportation ecosystem.

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