Reliability Modeling, Analysis, and Improvement of Telemetry and Remote-Control Systems

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Abstract
The research article focuses on improving the performance and reliability of telemetry and remote-control systems. Its primary objectives include developing reliability models to predict failures, analyzing potential failure modes through techniques like Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA), and implementing strategies like reliability-centered maintenance (RCM) and redundancy designs. Ongoing monitoring of reliability metrics is emphasized for data-driven decisions and maintaining optimal performance. The overarching goal is to foster a culture of reliability within development and operations to exceed safety and performance standards. The article details a conservative Markov modeling analysis of a digital feed-water control system (DFWCS) using NASA's Win SURE program, which showed a 99% probability of operational status over six months. It also presents a reliability improvement scheme for the telemetry remote control system (TRCS) aiming for Five Nines Availability (0.99999).

Keywords: Reliability modeling, Telemetry modeling improvement, Remote control systems, Markov, Availability, Evaluator.

مستخلص

تركز المقالة البحثية على تحسين أداء وموثوقية أنظمة القياس عن بُعد والتحكم عن بُعد. تشمل الأهداف الرئيسية تطوير نماذج موثوقية للتنبؤ بالأعطال، وتحليل أوضاع الفشل المحتملة من خلال تقنيات مثل تحليل وضع الفشل وتأثيراته (FMEA) وتحليل شجرة الأخطاء (FTA)، وتنفيذ استراتيجيات مثل الصيانة المعتمدة على الموثوقية (RCM) وتصميمات التكرار. يتم التأكيد على المراقبة المستمرة لمؤشرات الموثوقية من أجل اتخاذ قرارات مستندة إلى البيانات والحفاظ على الأداء الأمثل. الهدف الشامل هو تعزيز ثقافة الموثوقية ضمن التطوير والعمليات لتجاوز معايير السلامة والأداء. توضح المقالة تحليل نمذجة ماركوف التحفظي لنظام التحكم في المياه العذبة الرقمية (DFWCS)باستخدام برنامجNASA Win SURE ، والذي أظهر احتمال يصل إلى 99% للحالة التشغيلية على مدار ستة أشهر. كما تقدم خطة لتحسين الموثوقية لنظام التحكم عن بُعد للقياس (TRCS) تهدف إلى تحقيق توافر خمسة تسعات(0.99999) .

1. Introduction

Reliability refers to the likelihood that a product, system, or service will perform its intended functions effectively for a specified duration, or operate within a defined environment without failure [1], [2], and [3]. Control systems continuously monitor plant information and transmit commands to actuators [4], [5], and [6]. Dependability analysis of these systems aims to enhance performance, resilience, and output capacity, particularly by employing redundant structures to design robust engineering solutions [7] and [8].

Historically, assessing the reliability of complex digital systems comprising numerous components has relied on combinatorial mathematics. The conventional "fault tree" method of reliability analysis is founded on these mathematical principles. This method simplifies the problem by reducing the number of potential behaviors to consider for achieving a safe design, using a top-down approach to identify possible paths to undesirable states. However, the fault-tree method is inadequate for analyzing systems capable of reconfiguration, where the critical factor often becomes the efficiency of the dynamic reconfiguration process.

Failures can vary in severity; they may result in a complete loss of system functionality, rendering it unusable, or may simply indicate that an item has deviated beyond its specification limits while still remaining operational [9] and [10].

The failure may be critical in that there is a total loss of the function of the system and it can no longer be used or just that the item has gone out of its specification limits but can still be used.

For an item which is tested for a time t and when repaired each time it fails, then if it fails N times, the mean time between failures ($MTBF$) is:

$$MTBF = t/N \quad \ldots\ldots (1)$$

$$Failure\ rate\ \lambda = N/t = 1/MTBF \quad \ldots\ldots (2)$$

Usually, the exponential law is used to compute the Reliability, [11].

$$R = e^{-\lambda t}$$

$$\lambda = N/T$$

$$R \equiv Reliability$$

$$\lambda \equiv failure\ rate$$

$$N \equiv outages\ number\ over\ T,$$ [12].

The reliability of Telemetry and Remote-Control Systems (TRCS) is often overlooked, but this paper emphasizes the importance of addressing this critical aspect in the installation and operation of TRCS. The modeling and analysis of TRCS reliability focus on understanding the system's dependency and identifying the weak components that require improvement.

A Markov model for any given system is characterized by a list of its possible states, the transition paths between these states, and the rates associated with those transitions. In reliability analysis, these transitions typically involve failures and repairs. When visually represented, a Markov model uses “bubbles” to signify each state, while arrows illustrate the transition paths, as shown in Figure 1 below for a single component that can exist in either a healthy or failed state [13].

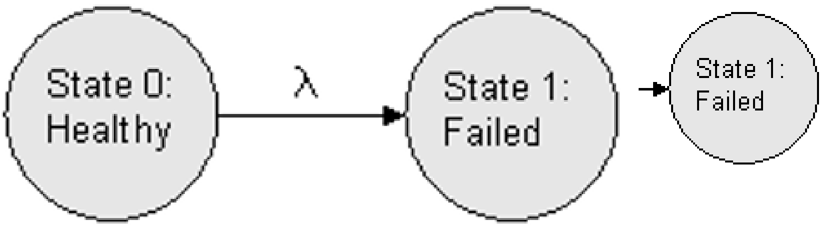

Figure 1: Markov Model for a Single Component

The objectives of the present research article focus on enhancing the performance and dependability of these critical systems. Firstly, the aim is to establish robust reliability models that accurately represent the operational behavior of telemetry and remote-control systems, enabling effective prediction of system failures and performance degradation over time. Secondly, the analysis objective seeks to identify and evaluate potential failure modes, their causes, and impacts, using techniques such as Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA), ultimately leading to a comprehensive understanding of system vulnerabilities. Thirdly, the objective is to implement improvement strategies through the application of reliability-centered maintenance (RCM) practices and redundancy designs, which enhance system resilience and minimize downtime during operations. Additionally, ongoing monitoring and assessment of system reliability metrics are crucial objectives, allowing for data-driven decision-making and proactive adjustments to maintain optimal performance. Finally, the overarching goal is to foster a culture of reliability within the development and operational processes, ensuring that telemetry and remote-control systems not only meet but exceed safety, performance, and reliability standards.

2. Overview

All transitions in the reliability model are deducible from its architecture. This measurability is the main consideration in developing a model for a digital system. The transitions of a fault-tolerant system are divided into two categories: slow failure transitions and fast recovery transitions. If the states of the model are defined properly, then the slow failure transitions can be obtained from the field data. The primary problem is to model the system so that the determination of these transitions is as easy as possible. If the model has many detailed states, the number of transitions that must be measured can be exorbitant and it will enlighten the expectations results of designing reliability and safety model of a digital feed water control system. We used the computer program SURE (Semi-Markov Unreliability Range Evaluator) [12] and [13] to solve reliability model numerically with Markov Model to design fault tolerant Digital Feed-Water Control System (DFWCS) used to control the input water level in its associated steam generator.

Digital Feed-Water Control System (DFWCS) is used to control the input water level in its associated steam generator [14] from approximately 1% reactor output power up to 100% reactor output power. DFWCS is basically divided into four divisions: sensors module, fault-tolerant group1 module, fault-tolerant group2 module, and actuators module. Fault tolerance techniques based on redundancy management are typically used to detect the fault occurrence in digital systems. The redundancy can either be in time, or in hardware, which is called passive redundancy and used to identify the permanent faults occurring in combinational logic circuits [14] and [15].

For computation of communication network's reliability based on service interrupt, it has mathematically modeled the reliability as an exponential growth depends mainly on the value of the failure rate throughout a year or 8760 hours [16]. For the reliability analysis of tracking, telemetry and command (TT and C) and communication systems, most existing modeling methods can only deal with general TT and C and communication tasks. A formal description of TT and C and communication task is given to facilitate the reliability modeling of such systems. A continuous-time Markov chain (CTMC) model is built for an idle task arc. A model for TT and C and communication tasks in consecutive flight cycles is proposed, in which the tasks are combined to a new complicated one [17].

A fusion model of anomaly detection with probability prediction and the Markov chain model was proposed to mitigate the isolated false alarms and improve the detection rate for collective anomalies. Firstly, compared with the single labelling strategy, the Markov chain model was trained with the sliding window to label the whole subseries. The introduction of sliding window to Markov chain can decrease the isolated false positives in telemetry series. Furthermore, given the independent assumption of the points within the testing sliding window, the sliding window fusion labelling cannot model the abnormal mode formed by points. The proposed fusion method can compute the transmission probability of the testing sliding window, which improves the detection rate for the collective anomalies. The experiments on the simulated data sets verified the performance improvement on the isolated false alarms and detection rate for the collective anomalies. In particular, the testing on the normal telemetry series and the abnormal telemetry showed the real applicability for anomaly detection of the telemetry [18].

The overall Reliability of a network are computed based on failure probability experienced from the network's reported outages. Reliability computation is independent on time; instead, it reflects the number of outages and their impact on providing the network success. Availability takes the duration of the failure rather than the number of failures encountered [16].

3. Conclusions

To embody the system telemetry, a number of methods of modeling including: Bayesian model and Monte Carlo…etc., can be used but in this paper Markov model is better to use because it consists of a list of the possible states of that system, the possible transition paths between those states, and the rate parameters of those transitions. In reliability analysis the transitions usually consist of failures and repairs.

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