Maximize System Reliability for Long Lasting and Continuous Applications

Chunhui Guo[1], Hao Wu[1], Xiayu Hua[1], Shangping Ren[1], Jerzy Nogiec[2]
[1]Illinois Institute of Technology, Chicago, IL 60616, USA
[2]Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
{cguo13, hwu28, xhua}@hawk.iit.edu, ren@iit.edu, nogiec@fnal.gov

Abstract

In this paper, we use software rejuvenation as a preventive and proactive fault-tolerance technique to maximize the level of reliability for continuous and safety critical systems. We take both transient faults caused by software aging effects and network transmission faults into consideration and mathematically analyze the optimal software rejuvenation period that maximizes system's reliability. The theoretical result is verified through empirical studies.

Introduction

Reliability is a critical criteria for many computer applications, specially for systems that directly interact with physical environment. For long lasting and continuous applications, such as factory control systems and deep space exploration vehicles, software aging caused system performance degradations, such as increased resource usage or prolonged execution time, can result in catastrophe consequences. Maintaining long lasting and continuous system's reliability has been both a research and an engineering challenge for many years.

To provide evidences for slowdown phenomena caused by software aging, we have conducted a simple experiment which opens and closes the Matlab R2012b and records the Matlab startup time. The test program is the only application running on the test machine. Fig. 1 shows the measurements of the Mathlab startup times over a week. Each time points represents the average Matlab startup time over 6-hour time interval. As shown in the figure, opening the Matlab takes 10% more time than when the system starts a week ago.

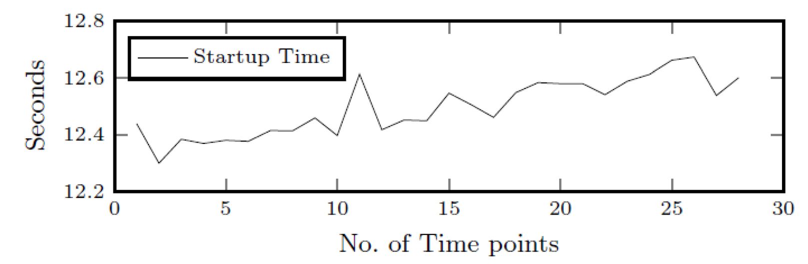

Fig. 1 Aging Effect on Matlab Startup Time

Fault-tolerance is a widely studied topic for ensuring system reliability. Commonly used fault-tolerance mechanisms include time redundancy, such as check-pointing and re-execution, and space redundancy, such as replication and voting. However, all these mechanisms tend to improve the system reliability in a passive way, i.e., they handle faults after their occurrences. Other than the passive fault-tolerance methods, another group of mechanisms are proposed to proactively improve the system reliability, such as fault prediction and software rejuvenation.

In this paper, we present an approach that uses software rejuvenation to maximize long lasting and continuous (24*7) system's reliability. Different from existing work in the literature, we take both transient faults caused by software aging and network transmission faults when migrating tasks between two processors into consideration, and decide an optimal software rejuvenation period that maximizes system reliability.

System Models

System State Transition Model

As shown in Fig. 2, the system has four states: Robust State S_0, Failure Probable State S_P, Failure State S_F, and Rejuvenation State S_R. The system is unavailable when it goes through either reboot or rejuvenation process.

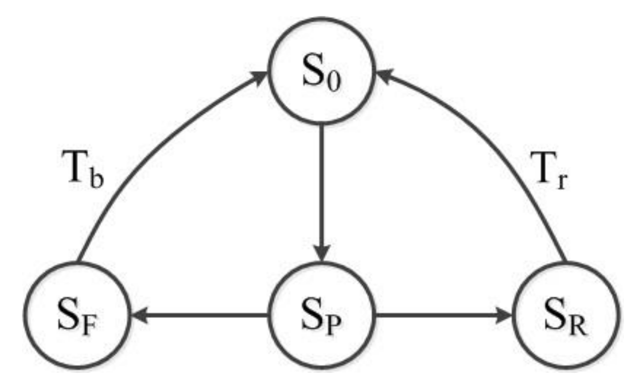

Fig. 2 System State Transition Model with Rejuvenation

System Model

As shown in Fig. 3, the system contains two processors: P_1 and P_2. Both processors can execute application tasks, but we assume that only one processor works on the application tasks at any given time, while the other processor either being idle or performing system maintenance.

To avoid failure caused by software aging effects, we assume that both processors perform rejuvenation periodically with a period t_s.Before one processor starts a rejuvenation process, it must first migrate all its tasks to the other processor.

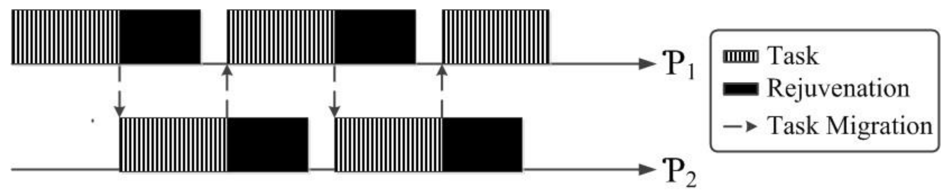

Fig. 3 System Model

Network Failure Model

We assume the network transmission failure model follows Poison distribution, i.e., it has a constant failure rate γ_0. The task migration between P_1 and P_2 may fail because of network transmission failures. With constant network transmission failure rate, the probability of a successful task migration is hence a constant ρ and does not change over time.

Aging Model

Since transient faults are more frequent than permanent faults, we only consider the transient faults for both processors. As the system deteriorates with aging, we assume that the transient failure rate $\gamma(t)$ increases with time t. The CDF (Cumulative Distribution Function) of transient fault is modeled as $F(t) = 1 - e^{-\int_0^t \gamma(x)dx}$.

After each rejuvenation, the system is as good as new, i.e., the failure rate and the cumulative distribution function after rejuvenation are reset to 0. Fig. 4 illustrates the behaviors of system rejuvenation and failure rate.

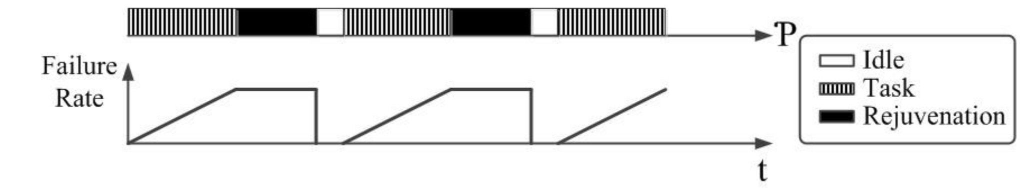

Fig. 4 System Rejuvenation and Failure Rate

Problem Formulation

Based on the models and assumptions, the system reliability decreases over time because of the increased failure rate caused by software aging. To maintain system reliability level, on one hand, the system should perform rejuvenation as frequently as possible, but on the other hand, every rejuvenation requires tasks being migrated to and back from the other processor. Due to unreliable network, frequent migration between processors can negatively affect the system reliability. Hence, there is a balanced point as to how frequently the system shall perform rejuvenation so that the system reliability can be maximized.

Problem. *Given two processors P_1 and P_2 which are connected through a network. Assume the transient failure rate of both processors is $\gamma(t)$, the network transmission failure rate is γ_0, and the system is to operate for L time, determine an optimal rejuvenation period t_s that maximizes the system reliability $R(L, t_s)$ within its operation interval $[0, L]$.*

System Reliability Maximization

Reliability

The system reliability within its longevity interval $[0, L]$ is

$$R(L, t_s) = \rho^{2(\lceil \frac{L}{t_s} \rceil - 1)} \cdot \overline{F(t_s)}^{\lceil \frac{L}{t_s} \rceil - 1} \cdot \overline{F(t')} \quad (1)$$

where $t' = L - t_s \cdot (\lceil L/t_s \rceil - 1)$ and $\overline{F(t)} = 1 - F(t)$.

Lemma 1. *Let system longevity be L and rejuvenation period be t_s, if $L \bmod t_s = 0$, then the system has the lowest reliability given by Eq. (2).*

$$R(L, t_s) = \rho^{2(\frac{L}{t_s} - 1)} \cdot \overline{F(t_s)}^{\frac{L}{t_s}} \quad (2)$$

■

For the following analysis, we focus on the worst case reliability, i.e., Eq. (2).

Reliability Maximization

Based on Eq. (2), system reliability is a function of two variables, i.e., L and t_s. To identify the relationship between reliability and rejuvenation period, we derive the partial derivative of $R(L, ts)$ with respect to the variable t_s. Let $\frac{\partial R}{\partial t_s}(L, ts) = 0$, we have

$$\frac{t_s}{\overline{F(t_s)}} \cdot \frac{\mathrm{d}\overline{F(t_s)}}{\mathrm{d}t_s} - \ln\overline{F(t_s)} - 2 \cdot \ln\rho = 0. \quad (3)$$

As Eq. (2) is a concave function, the optimal rejuvenation period that maximizes the system reliability can be calculated by solving Eq. (3) with given $\gamma(t)$ and ρ.

Lemma 2. *The optimal rejuvenation period is only influenced by network transmission failure rate γ_0 and transient fault occurrence rate $\gamma(t)$, but not by system longevity L.* ■

The **Weibull distribution** is commonly used to model the distribution of transient faults, with failure rate $\gamma(t) = kt^{k-1}/r^k$ and cumulative distribution function $F(t) = 1 - e^{-(t/r)^k}$, where $r > 0$ and $k > 0$ are scale and shape parameters. The failure rate increases with time t if $k > 1$.

Based on the models and assumptions, we use **Weibull distribution** with $k > 1$ to model aging effects. The optimal rejuvenation period that maximizes the system reliability is

$$t_s^* = \sqrt[k]{\frac{2 \cdot r^k \cdot \ln\rho}{1 - k}} \quad (4)$$

Experimental Results

We empirically evaluate the relationship between rejuvenation period and system reliability. In the experiments, we assume the probability of a successful task migration between two processors is $\rho = 0.99999$ and the system transient fault distribution follows **Weibull distribution** with $r = 1000$ and $k = 3$, i.e., $\gamma(t) = 3t^2/10^9$ and $F(t) = 1 - e^{-(t/1000)^3}$.We set rejuvenation period ranging from 1 to 100, and system operation time $L = 100$, and $L = 1000$, respectively.

Fig. 5 shows the system reliability under different rejuvenation periods for both longevity settings. The experimental results are consistent with our theoretic analysis.

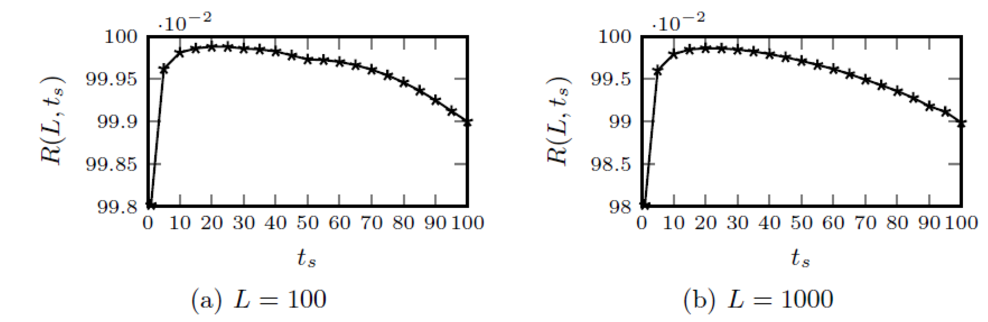

Fig. 5 Reliability vs Rejuvenation Period

Conclusion

Preventive and proactive fault-tolerance techniques are needed to maintain system reliability for long lasting and continuous applications. In this paper, we use both backup and software rejuvenation mechanisms to maximize system's reliability. In our study, we take both transient faults caused by software aging and network transmission faults into consideration and have mathematically analyzed the optimal rejuvenation period that maximizes system reliability. The empirical study confirms with the theoretic analysis.

Acknowledgement

The research is supported in part by NSF under grant number CAREER 0746643, CNS 1018731, and CNS 1035894.