하나의 이상구간을 가지는 테스팅 단계에서의 소프트웨어 신뢰도 성장 모형화

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요 약

소프트웨어 산업에서 고신뢰성의 소프트웨어 시스템을 생산하고 그들의 성능을 평가하는 일이 중요한 관심사항이 되어왔다. 소프트웨어의 평가는 주로 소프트웨어 시스템의 신뢰성과 성능의 양쪽 관점에서 수행되어져 왔다. 소프트웨어 신뢰도는 소프트웨어 테스팅 단계 동안에 한 고정된 시간구간에서 소프트웨어 오류가 발생하지 않을 확률을 말한다. 이들 이론적인 소프트웨어 신뢰성 모델들은 가끔 어떤 특정한 테스팅 구간에서는 하나의 어떤 소프트웨어 오류가 발생하여 소프트웨어 오류를 디버깅하여도 소프트웨어 고장율이 불완전 디버깅, 비정상적인 소프트웨어 수정 등등의 원인에 의해서 감소되어 실제적인 소프트웨어 테스팅 단계에서는 적당하지 않을 수도 있다. 이와 같이 부적당한 소프트웨어 테스팅 구간은 하나의 이상치 스테이지로 고려되어질 필요성이 있다. 이 이상치 소프트웨어 테스팅 구간에서만은 장애요인에 의해서 소프트웨어 신뢰도가 개선이 되지 않는다고 가정한다. 이와 같은 가정아래서 본 연구에서는 우선 소프트웨어 신뢰도 성장 모형에서 가장 많이 활용되는 Jelinski-Moranda모델을 변경하여 하나의 미지정된 이상치 소프트웨어 테스팅 구간을 고려하여 베이지안 방법에 의한 소프트웨어 신뢰도를 모형화하고 그 모형에 따른 소프트웨어 신뢰성 측도들을 추정하는 절차를 연구하였다. 그리고 제곱오차 결손함수의 조건아래 사전정보를 가정한 소프트웨어 신뢰도 모수의 베이즈 추정량을 제안하고, 제안된 소프트웨어 신뢰도 성장 모델을 하나의 이상치 소프트웨어 테스팅 구간상에 고려된 장애 모수의 값에 따라서 정확성, 바이어스, 추세 및 노이즈 등의 정량적인 평가 측도들을 사용하여 컴퓨터 시뮬레이션을 통하여 평가하였다.

Software Reliability Growth Modeling in the Testing Phase with an Outlier Stage

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ABSTRACT

The production of the highly reliable software systems and theirs performance evaluation have become important interests in the software industry. The software evaluation has been mainly carried out in terms of both reliability and performance of software system. Software reliability is the probability that no software error occurs for a fixed time interval during software testing phase. These theoretical software reliability models are sometimes unsuitable for the practical testing phase in which a software error at a certain testing stage occurs by causes of the imperfect debugging, abnormal software correction, and so on. Such a certain software testing stage needs to be considered as an outlying stage. And we can assume that the software reliability does not improve by means of nuisance factor in this outlying testing stage. In this paper, we discuss Bayesian software reliability growth modeling and estimation procedure in the

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presence of an unidentified outlying software testing stage by the modification of Jelinski-Moranda. Also we derive the Bayes estimators of the software reliability parameters by the assumption of prior information under the squared error loss function. In addition, we evaluate the proposed software reliability growth model with an unidentified outlying stage in an exchangeable-outlier model according to the values of nuisance parameter using the accuracy, bias, trend, noise metrics as the quantitative evaluation criteria through the computer simulation.

1. Introduction

In the software engineering field, the production of the highly reliable software systems and theirs performance evaluation have become important interests. Especially the software reliability estimation and prediction are of quintessence during the software development life cycle to increase the opportunity that software systems will perform satisfactorily.

Assuming that the perfect debugging of software errors, the software reliability which is the probability that no software error occurs for a fixed time interval increases during the software testing phase. This phenomenon is known as software reliability growth ([3], [9], [13], [22-27], [37]). In spite of the fact that Jelinski and Moranda model has been known as the best software reliability growth model proposed in the literature over two decades. This model has some problems that all remaining software errors contribute the same amount to the software failure intensity, and the maximum likelihood estimates of the software reliability metrics are used to be unstable and sometimes unreasonable ([11], [12], [16], [17], [31]).

To solve these problems, many software reliability engineers have used the Bayesian techniques and proposed many Bayesian software reliability growth models by the use of the observed software failure time data and the various prior information of the unknown software reliability parameters ([4], [7], [8], [18], [19], [28],[30], and so on).

Until now, Bayesian software reliability models have mainly dealt with the reliability growth concept throughout the perfect error debugging at each testing stage. But these models are sometimes unsuitable for the practical testing phase in which a certain software error occurs by causes of the imperfect debugging, abnormal software correction, and so on at each testing stage. Such a software testing stage is considered to be an outlying stage. And the software reliability does not improve in this outlying testing stage. Therefore, we discuss Bayesian software reliability growth modeling and estimation procedure in the presence of an unidentified outlying software testing stage by the modification of Jelinski-Moranda model which has been well-known as the simplest software reliability growth model.

In this paper, we first give the description of the Bayesian software reliability growth model with an unidentified outlying software testing stage in the software testing stage. And we derive the Bayes estimators of the software reliability parameters by the assumption of prior information under the squared error loss function. In addition, we evaluate the proposed software reliability growth model with an unidentified outlying stage in an exchangeable-outlier model. We compare estimates of accuracy, bias, trend, noise metrics as the quantitative evaluation criteria of the proposed software reliability growth model according to the values of nuisance parameter through the computer simulation.

2. Software Reliability Growth Modeling in Consideration of an Outlying Testing stage

Jelinski-Moranda model has been well-known as the software reliability growth model, which is the simplest, and the basic model to be generalized, but the model has some problems on the maximum likelihood estimates of the software reliability parameters. Many researchers have studied the Bayesian formulations of the Jelinski-Moranda model.

The Bayesian inference of this software reliability parameters N, the number of initial errors, and Φ, the failure intensity per an error, can be easily derived by assigning prior distributions to them. The parameters of the Jelinski-Moranda model are treated as random variables. For a given N and Φ, the i-th interfailure time $t_i = x_i - x_{i-1}$ is independently and exponentially distributed with parameters N and $\Phi = \phi$, that is the pdf of t_i can be written as

$$f(t_i) = (N-i+1)\phi \exp(-(N-i+1)\phi t_i),$$
$$i = 1, 2, \ldots m, \cdots\cdots\cdots\cdots (1a)$$

and the prior information to N and ϕ can be assigned. But this model is sometimes unsuitable for the practical testing phase in which a certain software error occurs and the failure rate does not decrease by causes of the imperfect debugging, abnormal software correction, and so on at a specific testing stage. Hence, we shall introduce a software reliability growth model in consideration of an unidentified outlying testing stage in the testing phase.

For a given N, ϕ and the fixed value r_0 of nuisance papameter, if the j-th testing stage is an outlying testing stage, the pdf of t_i is given by

$$f(t_i \mid r_0) = (N-i+1)\frac{\phi}{r_0} \exp(-(N-i+1)\frac{\phi t_i}{r_0}),$$
$$i = j, \cdots\cdots\cdots\cdots\cdots (1b)$$

where N is the number of initial errors and ϕ is the failure intensity per an error. And we will assume the prior information for N and Φ as follows;

[A1] N is distributed as Poisson,
[A2] Φ is distributed as Gamma, and
[A3] N and Φ are independent.

3. Bayesian Estimation for Software Reliability Parameters in an Exchangeable-Outlier Model with an Unidentified Outlying Testing Stage

Let $D_{t_m} = \{t_1, t_2, \ldots, t_m\}$ be the observed successive interfailure times for the test is monitored until the m-th software failure. If we consider that j-th testing stage is an unidentified outlying testing stage with probability 1/m in the software testing phase, the joint density of can be written as

$$f(x_1, x_2, \ldots, x_m) = \frac{1}{m} \sum_{i=1}^{m} f(x_i \mid r_0) \prod_{\substack{i=1 \\ j \neq i}}^{m} f(x_j).$$

As the likelihood function for parameters is equivalent to the joint density for random variabes, the likelihood function for N=k and $\Phi = \phi$ given D_{t_m} is given by

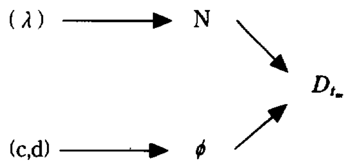
$$L(N = k, \Phi = \phi \mid D_{t_m})$$
$$= \frac{1}{mr_0}[\prod_{i=1}^{m}(k-i+1)]\phi^m \exp(-\phi\sum_{i=1}^{m}(k-1+1)t_i)$$
$$\sum_{j=1}^{m} \exp(-\phi(1-\frac{1}{r_0})kt_j), \cdots\cdots\cdots (2)$$

where r_0 is a fixed value of the nuisance parameter r.

For the hierarchical Bayesian approach, we consider the following prior information.

[P1] N and Φ are independent,
[P2] N has a poisson distribution P(λ), and
[P3] Φ has a gamma distribution G(c,d) with mean c/d.

By the Gibbs sampler[29], we consider the following generating directed graph.



Thus the prior distributions are given by

$$g_1(N=k)=\lambda_k\frac{\exp(-\lambda)}{k!},\ \lambda>0,\ k=1,2,\ldots,$$

$$g_2(\phi)=\frac{d^c\phi^{c-1}\exp(-d\phi)}{\Gamma(c)},\ c,d>0,\ \phi>0. \qquad \cdots\cdots\cdots\cdots\cdots (3)$$

And the joint posterior distribution of N=k and $\Phi=f(N=k,\Phi=\phi\mid D_{t_m})$ ϕ given sofywore inter-failure times set D_{t_m} can be written as

$$=\frac{L(N=K,\Phi=\phi\mid D_{t_m})g_1(N=k)g_2(\phi)}{\sum_{k=m}^{\infty}\int_0^{\infty}L(N=k,\Phi=\phi\mid D_{t_m})g_1(N=k)g_2(\phi)d\phi}$$

$$=\frac{[\frac{1}{mr_0}(\prod_{i=1}^{m}(k-i+1))\phi^m\exp(-\phi\sum_{i=1}^{m}(k-i+1)t_i)\sum_{j=1}^{m}\exp(-\phi(\frac{1}{r_0}-1)kt_j)]\frac{\lambda^k\exp(-\lambda)}{k!}\frac{d^c\phi^{c-1}\exp(-d\phi)}{\Gamma(c)}}{\sum_{k=m}^{\infty}\int_0^{\infty}[\frac{1}{mr_0}(\prod_{i=1}^{m}(k-i+1))\phi^m\exp(-\phi\sum_{i=1}^{m}(k-i+1)t_i)\sum_{j=1}^{m}\exp(-\phi(\frac{1}{r_0}-1)kt_j)]\frac{\lambda^k\exp(-\lambda)}{k!}\frac{d^c\phi^{c-1}\exp(-d\phi)}{\Gamma(c)}d\phi} \qquad \cdots\cdots\cdots\cdots\cdots (4)$$

where N=k>m>0, $\phi>0$, $0<r_0\le 1$, $\lambda>0$ and c, d>0.

The marginal posterior distribution of N=k is given by

$$f(N=k\mid D_{t_m})$$

$$=\int_0^{\infty}f(N=k,\ \Phi=\phi\mid D_{t_m})d\phi$$

$$=\frac{[\prod_{i=1}^{m}(k-i+1)]\frac{\lambda_k}{k!}\sum_{j=1}^{m}\sum_{i=1}^{m}(k-i+1)t_i+(\frac{1}{r_0}-1)kt_j+d]^{-(m+c)}}{\sum_{k=m}^{\infty}[\prod_{i=1}^{m}(k-i+1)]\frac{\lambda^k}{k!}\sum_{j=1}^{m}\sum_{i=1}^{m}(k-i+1)t_i+(\frac{1}{r_0}-1)kt_j+d]^{-(m+c)}} \qquad \cdots\cdots\cdots\cdots\cdots (5)$$

And the marginal posterior distribution of $\Phi=\phi$ is as follows.

$$f(\Phi=\phi\mid N=k,D_{t_m})$$

$$=\frac{f(N=k,\Phi=\phi\mid D_{t_m}}{f(N=k\mid D_{t_m}}$$

$$=\frac{1}{r(m+c)}\sum_{j=1}^{m}[(k-i+1)t_i+(\frac{1}{r_0}-1)kt_j+d]^{(m+c)}\phi^{(m+c-1)}$$
$$\times\sum_{j=1}^{m}\exp(-\phi[\sum_{i=1}^{m}(k-i+1)t_i+(\frac{1}{r_0}-1)kt_j+d]). \qquad \cdots\cdots\cdots\cdots\cdots (6)$$

By the Bayes rule, we can obtain the Bayes estimators of N=k and $\Phi=\phi$;

$$k^{BE}=E[N=k\mid D_{t_m}]$$

$$=\sum_{k=m}^{\infty}kf(N=k\mid D_{t_m})$$

$$=\frac{\sum_{k=m}^{\infty}[\prod_{i=1}^{m}(k-i+1)]\frac{\lambda^k}{(k-1)!}\sum_{j=1}^{m}(k-i+1)t_i+(\frac{1}{r_0}-1)kt_j+d]^{-(m+c)}}{\sum_{l=m}^{\infty}[\prod_{i=1}^{m}(l-i+1)]\frac{\lambda^l}{l!}\sum_{j=1}^{m}\sum_{i=1}^{m}(l-i+1)t_i+(\frac{1}{r_0}-1)lt_j+d]^{-(m+c)}} \qquad \cdots\cdots\cdots\cdots\cdots (7)$$

and

$$\psi^{BE}=E[\Phi=\psi\mid N=k,D_{t_m}]$$

$$=\int_0^{\infty}\psi f(\Phi=\psi\mid N=k,D_{t_m})d\psi$$

$$=\frac{m+c}{\sum_{j=1}^{m}\sum_{i=1}^{m}(k-i+1)t_i+(\frac{1}{r_0}-1)kt_j+d]} \qquad \cdots\cdots\cdots\cdots\cdots (8)$$

Therefore the Bayes estimator of the current software reliability after the m-th software failure occurs is given by

$$R^{BE}(t_m)=E[R(t_m)\mid D_{t_m}]$$

$$=\sum_{k=m}^{\infty}\int_0^{\infty}\exp(-\psi t_m)f(N=k,\Phi=\psi_{t_m}\mid D_{t_m})d\psi$$

$$=\frac{\sum_{k=m}^{\infty}[\prod_{i=1}^{m}(k-i+1)]\frac{\lambda_k}{k!}\sum_{j=1}^{m}[\sum_{i=1}^{m}(k-i+1)t_i+(\frac{1}{r_0}-1)kt_j+d]+t_m]^{-(m+c)}}{\sum_{k=m}^{\infty}[\prod_{i=1}^{m}(k-i+1)]\frac{\lambda^k}{k!}\sum_{j=1}^{m}\sum_{i=1}^{m}(k-i+1)t_i+(\frac{1}{r_0}-1)kt_j+d]^{-(m+c)}} \qquad \cdots\cdots\cdots\cdots\cdots (9)$$

where $0<r_0\le 1$, $\lambda>0$ and c, d>0

4. Model performance evaluation by computer puter simulation

In order to evaluate the proposed software reliability growth model which has an outlying testing stage in terms of objectiveness and quantitativeness according to the amount of nuisance, we can use four formally defined equation metrics([1], [6], [7], [10], [15], [20], [21], and [33]). These quantitative metrics are accuracy, bias, trend, and noise representing the performance evaluation criteria of the software reliability measurement from the proposed model.

- Accuracy

Let $D_{t_m}=\{t_1, t_2, \ldots, t_m\}$ be the observed successive interfailure times. The objective is to use the test data to predict the future unobserved interfailure time T_j. For such one-step-ahead predictions of T_{j+1}, ..., T_{j+n}, the prequential likelihood as the accuracy metrics is given by

$$PL_n=\prod_{i=j+1}^{j+n}\frac{d}{dt}\hat{F}_i(t), \qquad \cdots\cdots\cdots\cdots (10)$$

where $F_i(t)=\Pr(T_i < t)$ and $\hat{F}_i(t)$ is the estimate of $F_i(t)$.

Since this metrics is usually very close to zero, we can take its logarithmic value for performance evaluation of the proposed model. Because the values are always negative, the smaller the values are, the more accurate the models are.

- Bias

By the Kolmogorov distance, we can define the bias metrics as as following sequence of transformation based on $\{t_1, t_2, \ldots, t_{i-1}\}$.

$$u_i=\hat{F}_i(t_i), \qquad \cdots\cdots\cdots\cdots (11)$$

where u_i would be realization of independent uniform random variables, and the smaller the absolute values of u_i are, the less bias the models exhibits.

- Trend

Trend metrics can be written as

$$y_i=\frac{\sum_{j=1}^{i}x_j}{\sum_{j=1}^{m}x_j}, \qquad \cdots\cdots\cdots\cdots (11)$$

where $x_i=-\ln(l-u_i)$ is the sequence of transformation based on the bias metrics u_i, A small means that the model is more adaptable to change in the behavior of the software failure time data.

- Noise

By Braun statistics, we can define the noise metrics as follows.

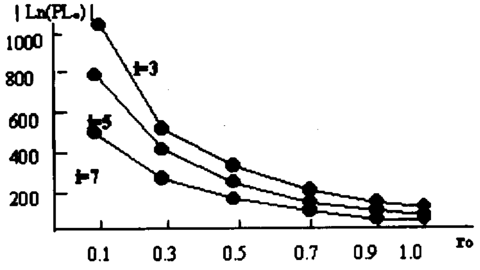
$$N_s=\sum_{i=1}^{m}\left|\frac{M_i-M_{i-1}}{M_{i-1}}\right|, \qquad \cdots\cdots\cdots\cdots (11)$$

where M_i is the predicted median of T_i. Small values represent less noise in the predictive behavior of the proposed model.

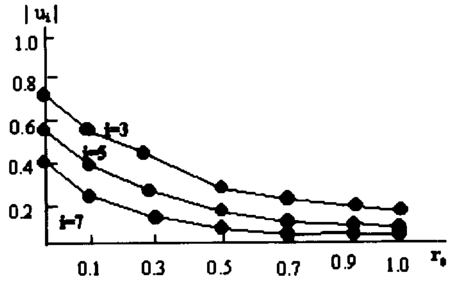
By the use of the above four evaluation criteria, we compare the mean values of the evaluation metrics on the proposed software reliability growth model with an outlying testing stage. We have carried out the computer simulation according to the values of the fixed nuisance parameter r_0=0.1(0.2)0.9, 1.0 based on 100 random samples as follwing procedures.

- (Procedure 1) Set the numbers of testing stages and set the values of parameters.
- (Procedure 2) Generate random variates and random samples.
- (Procedure 3) Calculate the values of four evaluation metrics.
- (Procedure 4) repeat 100 times from Procedure 2 to Procedure 3.
- (Procedure 5) Calculate the means of four evaluation metrics.

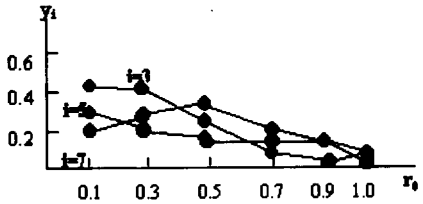
And we can see that the software testing phase has no an outlying testing stage when r_0=1.0. The evaluation results are shown in <Fig. 1>.



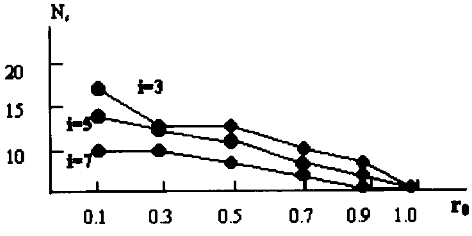
(a) The mean values of accuracy metrics



(b) The mean values of bias metrics



(c) The mean values of trend metrics



(d) The mean values of noise metrics

(Fig. 1) The tendency to evaluated values of quantitative metrics according to nuisance parameter r_0 when $\lambda=2$, c=3, d=4, m=10.

5. Conclusion and remarks

In this paper, we have introduce a Baysian approach of software reliability growth modeling in the case of an unidentified outlying testing stage in an exchangeable-outlier model. This outlying software testing stage is considered in which a certain software error occurs and the failure rate does not decrease by causes of the imperfect debugging, abnormal software correction, and so on, at an unidentified software testing stage. Also we propose Bayes estimators of the software reliability and related parameters by use of the fixed value of the nuisance parameter with an unidentified outlying software testing stage. We have only considered the fixed value of nuisance parameter for an outlying software testing stage because integral calculation was very cumbersome. Also we evaluate the proposed Bayesian software reliability growth model with an unidentified outlying testing stage according to the nuisance values in terms of accuracy, bias, trend and noise metrics as quantitative evaluation criteria through the computer simulation.

From (Fig. 1) which are summarized the evaluated values of accuracy, bias, trend and noise metrics according to r_0, we can get the following results:

- The accuracy and bias metrics are very sensitive on the values of nuisance parameter. And as we can expect, the closer to 1.0 the value of the nuisance parameter is, the better the performance of the model is.

- The trend and noise metrics are very robust on the values of nuisance parameter.

- The degree of outlying in testing stage can be well-represented by the nuisance density.

Therefore we conclude that we can consider the Bayesian software reliability growth model with an unidentified outlying software testing stage, and we can select the proper models by means of the values of nuisance parameter. In addition, we can evaluate software reliability in this case.

For the more efficient modeling of the software reliability growth in the presence of an outlying software testing stage, the following further study might be carried out.

- Nuisance parameter for an outlying software testing stage can be extended to be variable.

- The comparison of models can be performed in the cases that an outlying testing stage is excluded and an outlying testing stage is included.

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