Assessing the Reliability of Applications with Supervision Tree

Jiansen HE

1 Introduction

Libraries such as Erlang OTP [Ericsson AB., 2012], Akka[Typesafe Inc. (b), 2012], and TAkka are built with the belief that the reliability of a software application can be improved by using supervision tree, in which failed components will be restarted by their supervisor. Erlang OTP and Akka have been used in a number of applications that have achieved a high reliability. Could the reliability of a newly developed application be assessed in an effective manner? To what extend the usage of supervision tree contributes to the overall reliability?

To answer above questions, this proposal suggests a research roadmap as follows. Section 2 summarizes general methodologies used in the area of reliability studies. Focusing on the statistic approach to measure the reliability of software applications which are expected to have low failure rates, we propose to improve [Littlewood and Strigini, 1993]'s single-run experiment, summarized in Section 3.1, by using the iterative experiment (Section 3.2) when conditions apply. The iterative approach can reduce the experiment time and can be stopped when the desired belief about the reliability had been rejected. Aside from the methodology for directly assessing the reliability of a general application, this proposal also looks into approaches that indirectly assessing the reliability of application built using the supervision tree principle. Section 4 summarizes Nyström's approach for analysing the statical structure of Erlang supervision trees, and Jiansen's extensible work on dynamically monitoring TAkka supervision trees. Finally, the essence of a node in a supervision tree is abstracted as a Deterministic Finite Automaton

(DFA) in Section 5. The abstraction is used to model and compare designs of supervision tree in Erlang and (T)Akka, among alternatives that have not been adopted. A straightforward definition for the reliabilities of a node in a supervision tree is derived from the model. It remains to be seen whether i) the overall reliability of a supervising tree can be derived from the reliability of its nodes and the structure of that supervision tree, and ii) there exists an algorithm to aid the design of supervision tree with a high reliability.

2 Methodologies for Assessing Software Reliability

The reliability in this proposal is defined as the probability that a system can function properly for a specified period. Formally, the reliability function, $R(t)$, denotes the probability that a system can function properly for time t. In the study of software reliability, the period may be specified in term of *time units* (e.g. second) or *natural units* (e.g. number of operations) [Musa, 2004]. Reliability is usually reported in terms of failure rate (λ), Mean Time Between Failures (MTBF, $1/\lambda$), and other variants.

The reliability function, its failure density function $f(t)$, and MTBF has following relationships: [Musa, 2004]

$R(t) = \int_0^\infty f(x)dx$

$MTBF = \int_0^\infty tf(t)dt$

$MTBF = \int_0^\infty R(t)dt$

In literature, the precise definition of failures varies in the study of different systems. Failure in this proposal is a general term to describe the situation where a system or a sub-system does not work as specified.

Once the meaning of failure is defined for a specific application, measuring the reliability during a period is straightforward. The challenge is how to use the previous data, collected from experimental or operational environment, to give confidence about the reliability in the future under the operational environment.

For software which involves iterative debugging process, software reliability growth models are usually employed to capture the relationship between the bug removing process and the reliability improvement. [Abdel-Ghaly et al., 1986] examines 10 models in this area, and a framework to evaluate the effectiveness of different models.

For software that has reached certain level of reliability and hence the debugging process has minor effects, [Littlewood and Strigini, 1993] gives a Bayesian approach to validating its reliability. Because this approach targets at systems that have high reliabilities, we will discuss this approach in sufficient detail in the next section.

3 Statistic Approaches for Measuring Reliability

3.1 Littlewood's approach to predict software reliability.

The analysis in [Littlewood and Strigini, 1993] answers the following question: given that x failures are observed during the period of testing t_0, what can we conclude about the reliability in the next t time.

The two assumptions in Littlewood's approach are:

Assumption I) the occurrence of failures is a poisson process, that is, time between failures are independent.

Assumption II) the prior belief about the distribution of failure rate, $p(\lambda)$ follows the gamma distribution, $\mathrm{Gam}(\alpha, \beta)$, where α and β are positive hype-parameter that describes the sharp and the rate of the distribution.

Assumption I is an appropriate choice for general studies.

Since the posterior belief is adjusted by the observed data, the prior belief will have less effect on the posterior belief if sufficient evidence is collected from a long experiment. The Gamma distribution is chosen because it is the *conjugate distribution* for poisson distribution. It means that using the Gamma distribution as prior belief will result to a posterior belief which also follows the Gamma distribution. Particularly, if the prior belief is $\mathrm{Gam}(a, b)$, then posterior belief will be $\mathrm{Gam}(a + x, b + t_0)$, where x is the number of observed failures and t_0 is the experiment time. Littlewood and Strigini Alternatively, any probability distribution may be used to replace the Gamma distribution, if it better describes the property of the failure rate of a particular application.

Littlewood and Strigini then derives that the reliability function for the future t time is

$R(t|x,t_0) = \left(\frac{b+t_0}{b+t_0+t}\right)^{a+x}$

Littlewood and Strigini then concludes that "observing a long period of failure-free working does not in itself allow us to conclude that a system in ultra-reliable" from the analysis of two extreme cases. The first case is, choosing an improper prior so that the posterior completely depends on the data. The posterior itself is an proper distribution; however, after observing a period of failure-free operations, one has 50% possibility to be failure-free for the same amount of time in the future. The second example is, to claim a system has 10^6 hours (114 years) MTBF by showing 10^3 hours (41.7 days) of failure-free working, one must hold the prior belief that the system is a 10^6 system.

3.2 Reduce experiment time of the Littlewood and Strigini test?

In Littlewood and Strigini's study, prediction of the reliability is made according to the result of an earlier experiment under the same operational environment. In such an experiment, even a long-time failure free observation cannot conclude a high reliability for the future. This section attempts to solve three problems: i) based on the same assumptions about the failure rate, can we improve the experiment so that the expected reliability can be verified or rejected earlier? ii) can we validate the same basic assumptions used in Littlewood and Strigini's and the improved approach? iii) is it possible to claim a genuine prior belief about the distribution of the failure rate?

3.2.1 Iterative experiments

Assuming that the occurrence of failures is a poission process and the failure rate follows the Gamma distribution, representing the Gamma distribution using hyper-parameters, it is clear that the posterior belief about the failure rate, $Gam(a + x, b + t)$, depends on the prior belief $Gam(a, b)$, the *total* number of observed failures x, and the *total* experiment time t. Therefore, for an application that consists of a number of replica subsystems, we can replace Littlewood and Strigini's experiment with an equivalent iterative experiment described below.

An iterative experiment consists of several rounds of sub-experiments, each of which may consists of several parallel experiments. In an iterative experiment, the posterior belief of one round is used as the prior belief of the next round. Instead of asking whether a system will be reliable in the next 10^6 hours based on the failure rate of the first 10^3 hours [Littlewood and Strigini, 1993], the experiment conductor concerns whether the system will be reliable in the next round, based on the failure rate of previous results. In each iteration, a number of instances may be tested in parallel to collect the results of more instance hours within less time. An iterative experiment may be stopped as soon as the belief about the failure rate is disproved, or the base assumption about poisson process and Gamma distribution are rejected.

Take the above proposal into practise, assuming we are asked to test whether a distributed web service designed for an organisation will be as reliable as its developers claimed for the next a few years. We may run a test on one or two local machines for 1 day. If the result meets the requirement, then we may test the application on some servers of the organisation for half a week. Then, we may rent 1000 similar servers from one or more cloud service providers in the third round which lasts a week. By doing this, we can collect the number of failures occurred in an experiment of 168,000 instance hours within a week $(168,000 = 7 \times 24 \times 100)$. Fortunately, the data can be treated as equivalent to a result collected from a single-run experiment on one machine for 19 years $(19 = 168,000 \div 24 \div 365)$, if our assumptions are valid for tested system. Renting a thousand server instances might be expensive, but the risk of wasting resource on testing application that doesn't meet the desired reliability has been reduced in previous rounds of tests.

3.2.2 Verify Assumptions

Both Littlewood and Strigini's original approach and our alternative are based on the assumption that the occurrence of failures is a poisson process and the failure rate follows a Gamma distribution represented by two hyper-parameters. Those two assumings are good choice in a study for general purposes. For a test of a real application, to what extend can we rely on the assumption of poisson process and the prior belief with guessed hyper-parameters? To verify those assumptions, suitable goodness-of-fit tests can be used. Following are example approaches.

To verify the assumption on poission process, we can alternatively check whether the number of failures in consecutive fixed periods follows the poission distribution, whose mean and variance are the same. To verify the assumption on gamma distribution, [Woodruff et al., 1984] gives improved methodologies for the purpose of reliability test.

3.2.3 Obtain a genuine prior belief

Following is my guesswork. Appropriate statistic analysis is required.

If x failures are observed in the previous experiment of t time and the base assumption cannot be rejected by the data in previous tests, the **best** prior belief for the next iteration is assuming the distribution of failure rate λ follows Gam(x, t).

This is a significant difference between the iterative experiment and Littlewood and Strigini's single run experiment. In Littlewood and Strigini's approach, claiming a Gam(x, t) *posterior* is the same as claiming a improper *prior* Gam(a, b), where $a,\ b\ \to 0$. In an iterative experiment, the first round can be used to "generate" a reliable prior for the second round. However, at least 1 failure need to be observed in the first round because a and b in Gamma distribution are positive numbers. In a ultra-reliable system, waiting for the first occurrence of failure may take a long time.

3.2.4 Testing in adversely environment.

Another attempt to give a reliability prediction in short period is testing the system in adversely environment. This idea, known as accelerated testing (AT), has been explored in hardware reliability test for years [Escobar and Meeker, 2006], and has been applied to test the $FASTAR^{SM}$ platform, a set of systems used to automatically restore the AT&T network[Cukic, 1997].

An accelerated test consists of two general steps. The first step is to identify accelerating factors (e.g. temperature, workload, temperature etc.) and run the experiment. The second step is to use suitable regression model to predict the reliability in normal condition.

The significance of an accelerated testing depends on the choice of the regression model. For a hardware, the relationship between its life-time and environment factors (e.g. temperature) has been well studied. In the $FASTAR^{SM}$ test, to capture and verify the regression model, 32 runs are carried out under different pressure environment. Each run lasts for about 30 hours and a few failures are observed during the test.

Bring in the same idea into the test of TAkka applications, for example, with the help of the Chaos Monkey library, can we effectively test the reliability within a reasonable short period? Unfortunately not.

Let's run two experiments in parallel. In one experiment, ChaosMonkey is not used and its failure rate, λ_n, is assumed to be the same as in the normal operational environment. In the other experiment, ChaosMonkey is employed to increase the exception rate so that the failure rate, λ_c, will be higher than λ_n. Failure rates in the two experiments are linked by the following equation: $\lambda_n \times t_n = \lambda_c \times t_c$, where t_n and t_c are expect periods of seeing x failures in the normal environment and in the ChaosMonkey test.

The above equation shows that the expected time for the *nth* occurrence of failures decreases when its failure rate increased. Therefore, assumptions on the poission process and the Gamma distribution can be verified in shorter time. From a serials of ChaosMonkey test with different failure rates, we may fortunately find that the occurrence of failures in the tested application is always a poission process. As a result, to measure its reliability in normal operational environment, only a small number of errors need to be observed under the test in normal environment. However, it may take a long time to observe the first occurrence of failures in a system whose MTBF is 10^6 hours.

4 Reliability Studies on Supervision Tree

4.1 Static Analysis on Tree Structure

Based on the Core Erlang Language defined by [Carlsson et al., 2000], [Nyström, 2009] defines an abstract semantic to extract structures of Erlang programs. Since supervision tree is constructed in Erlang by calling callback functions in the *supervision* module, Nyström's work can be used to abstract the structure of supervision trees form the source code of Erlang applications.

Noted in the later part of Nyström's thesis, there are two limitations of his approach. Firstly, the abstraction only captures the static structure of the supervision tree, which may differ from its run-time structure. Secondly this approach requires specialised knowledge about the Erlang language and only applies to "applications that have been designed according to the suggestion of the OTP documentation and using the OTP library behavious." [Nyström, 2009].

4.2 Dynamic Monitoring

The supervision view library in the TAkka paper.

5 Modelling Supervision Tree

To study properties of supervision tree, a simple formal model is required to describe the essence of supervision tree. Section 5.1 models Worker and Supervisor and Deterministic Finite Automata (DFA). With this model, implementation alternatives of Supervision Tree are compared. More importantly, the model helps us to give a simple general definition for the reliability of nodes in a supervision tree. This section ends with a proposal for investigating the reliability of a supervision tree, based on the reliabilities of its nodes and the relationships between nodes.

5.1 Worker and Supervisor as Deterministic Finite Automata (DFA)

Figure 1 gives state graphs of DFAs that describe worker and supervisor in a supervision tree. Nodes in the graphs represent states of that DFA and arrows are transitions from one state to another. A transition is triggered either by the node itself or due to changes of the environment it resides.

At any time, a worker may be in one of its four states: **Start**, **Free**, **Blocked**, or **Dead**. After automatically being initialised to the **Free** state, the Work can accept messages from its outside environment and enters to the **Blocked** state where no messages will be processed. If no error occurred when processing the message, the worker emits a result and go back to the **Free** state. An error may occur during the middle of message processing (e.g. software bugs) or when the environment changes (e.g. hardware failures), in which cases the worker reports its failure to its supervisor and go to the **Dead** state. A dead worker can be resumed or restarted by its supervisor so that it can process new messages. **Free** and **Dead** are marked as accept states from which no further actions may occur. On the contrary, a **Blocked** worker will eventually emit a reply message or raise an exception; and all workers will be successfully initialised.

The DFA of a supervisor whose only duty is supervising its children is given in Figure 1(b). A supervisor in its **Free** state reacts to failure messages from its children. Meanwhile, a supervisor may fail at any time and reports its failure to its supervisor.

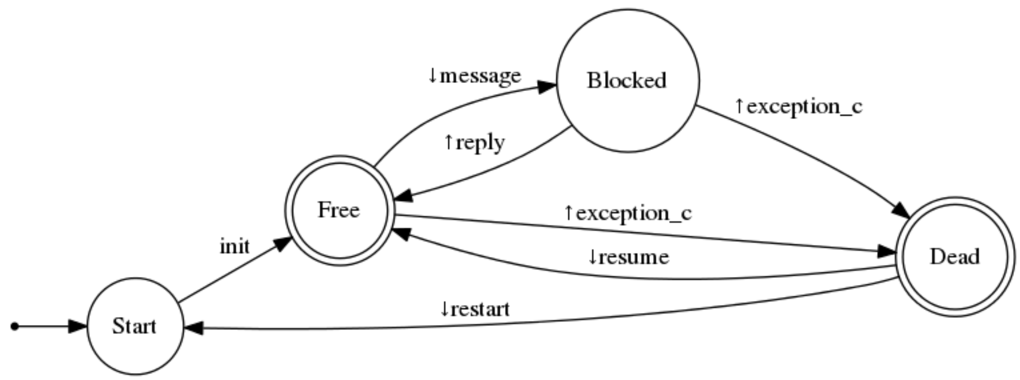
5.2 Implementation Considerations

The two DFAs given in Figure 1 are abstracted for theoretical study. In an implementation of the supervision tree model, following issues might be considered.

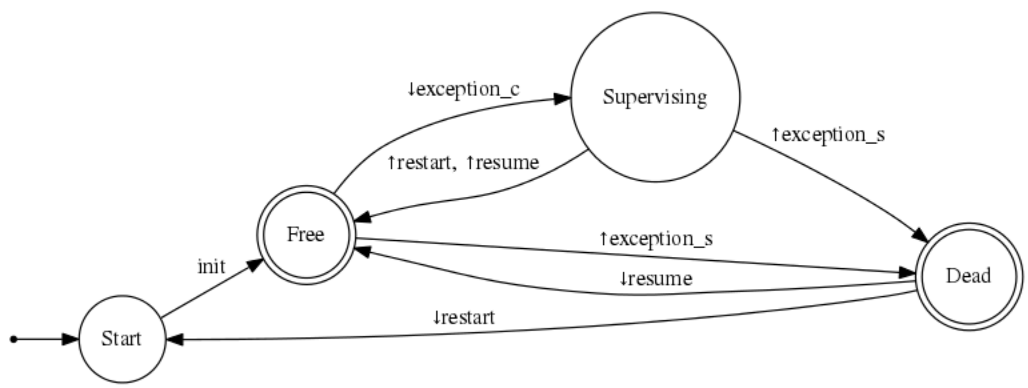
Distributed Deployment Supervision Tree represents the logic relationship between nodes. In practice, nodes of a supervision tree may be deployed in distributed machines. A child node may be restarted at or shipped to another physical or virtual machine but stays in the same place in the logic supervision tree.

Heart-Beat Message At run-time, failures may occur at any time for different reasons. In some circumstances, failure messages of a child may not be delivered to its supervisor, or even worse, not sent by the failed child at all. To built a system tolerant to the above failures, supervisors need to be aware of the liveness of their children. One approach to achieve this is asking the child periodically sending heart-beat message to its supervisor. If no heart-beat message is received from a child for some consecutive periods, that child is considered dead by the supervisor and an appropriate recovery process is activated. In the model, a logical exception is sent from a child to its supervisor when no heart-beat message is delivered within a time-out, and a restart or resume message is sent to a suitable machine where the node will reside.

Message Queuing In the simplified model given in Figure 1(a), a worker can processed one message a time when it is **Free**. The model does not exclude the case where messages are queuing either in memory or a distributed database. Similarly, when a worker is resumed from the failure of processing a message, the message it was processing may be retrieved from a cache or be discarded.



(a) Worker



(b) Supervisor

Figure 1: Worker and Supervisor as Deterministic Finite Automata

5.3 Unifying Supervisor and Worker

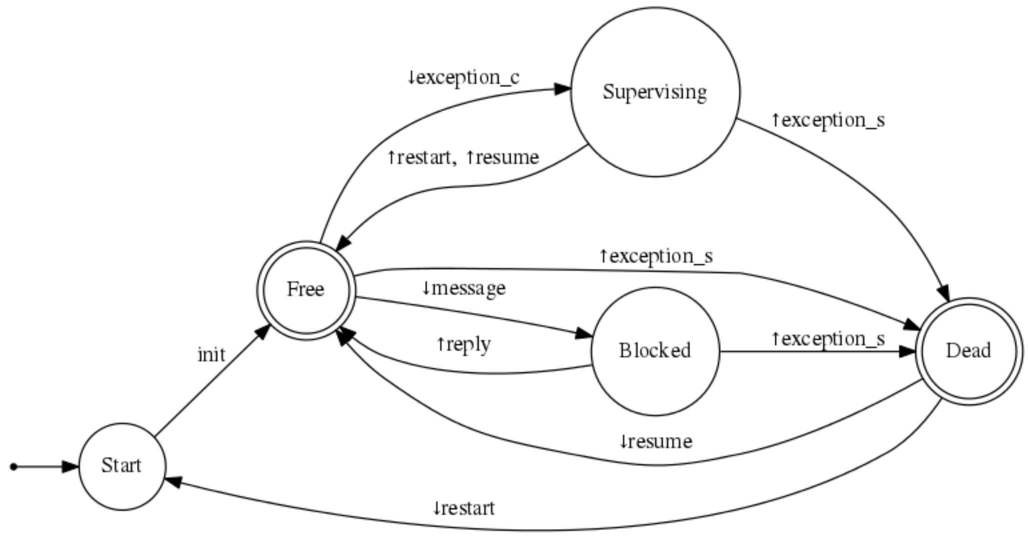
Notice that the model for supervisor and worker are similar if exceptions from the child is viewed as request messages to a supervisor and restart/resume is viewed as reply messages to a child. Can we defined a *combined* node which can be both a worker for a task and a supervisor for some children? Of course we can, as what have been implemented in Akka[Typesafe Inc. (b), 2012] and inherited by TAkka. The rest of this sub-section will compare three strategies of unifying supervisor and worker.

Supervisor as a Worker In the design of Akka, messages to actors are not typed. An Akka actor therefore can be both a supervisor and a worker. To model an Akka actor, only Figure 1(a) is required.

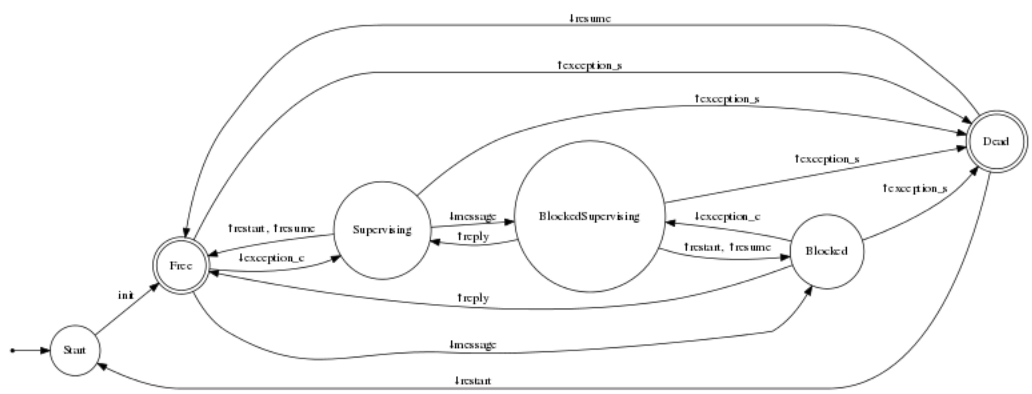
Combining Supervisor and Worker The TAkka library inherits the implementation of Akka, but separates messages for supervision purpose from messages for general purposes so that an actor can be parameterized by the type of message it expects. A more precise model for a TAkka actor is given in Figure 2(a). Both Akka actor and TAkka actor can only be a supervisor or a worker at a time. As a result, the supervision task may be blocked until the end of another computational task.

Supervisor in Parallel with Worker One way to get around the limitation of Akka and TAkka's design is place the supervision process and the worker process in parallel, as shown in Figure 2(b). From the perspective of model analysis, the above parallel model is equivalent to the one which separates the supervisor process and the worker process into two nodes, and treat them as siblings or a supervisor and a child.

To summarize, a node that naively combining the role of supervisor and worker (Figure 1(a) and 2(a)) has less availability than a node that place the supervision process and the worker process in parallel processes (Figure 2(b)). Interestingly, during the process of designing TAkka, we realized that the type of supervision messages should be separated from the type of other messages. However, partly because we would like to reuse the Akka implementation and partly because we did not have the above model at that time, the process of handling supervision messages is not separated from the process of handling other messages.



(a) Supervisor AND Worker



(b) Supervisor PAR Worker

Figure 2: A Node that Unifies Supervisor and Worker

5.4 Reliability of a Node

The reliability of a node, either a worker or a supervisor, is defined as:

The the probability that a node is in the **Free** state.

5.5 Reliability of a Supervision Tree

A supervision tree in this proposal consists of workers and supervisors defined in Figure 1(a) and Figure 1(b) respectively. A node that combines a supervisor and a worker is separated into two nodes, together with a constraint that one node will fail when the other fails.

The reliability of a supervision tree may be derived from following factors:

- The reliabilities of all workers. Although testing the reliability of a system with low failure rate is difficult or even impractical, the reliability of an individual component may be measured within a reasonable short time.

- The reliability of a supervisor. The reliability of a supervisor process may be tested as part of the library development process.

- The relationship between nodes. Nodes in a supervision tree may collaborate to perform a task or to achieve a higher reliability. The reliability of a supervising shall capture complex relationships between nodes.

The experiment proposed in section 3.2 may to used to measure the reliabilities of individual nodes in a supervision tree. To obtain the reliability of a supervision tree, when direct measurement becomes impractical, knowledge about constraints between nodes are required.

I propose to investigate following problems in the next stage:

- What are possible constraints between nodes? For each constraint, what is the algebraic relationship between the reliability of a sub-tree and reliabilities of individual nodes?

- Based on the above result, how to calculate the overall reliabilities of a supervision tree? When is the reliability is improved by using supervising tree, and when not?

- Given the reliabilities of individual workers and constraints between them, is there an algorithm to give a supervision tree that improves the reliability? If not, can we determine if the desired reliability is not achievable?

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