Prognostic & Health Management (PHM) Tool for Robot Operating System (ROS)

Date : 07.08.2019

TABLE OF CONTENTS

FIGURE LIST

TABLE LISTS

- EXECUTIVE SUMMARY

Nowadays, prognostics-aware systems are increasingly used in many systems and it is critical for sustaining autonomy. All engineering systems, especially robots, are not perfect. Absence of failures in a certain time is the perfect system and it is impossible practically. In all engineering works, we must try to predict or minimize/prevent failures in the system. Failures in the systems are generally unknown, so prediction of these failures and reliability of the system is made by prediction process. Reliability analysis is important for the improving the system performance, extending system lifetime, etc. Prognostic and Health Management (PHM) includes reliability, safety, predictive prognostic, fault detection / isolation, advanced diagnosis, component lifecycle tracking, health reporting and information management, etc.

This study proposes Prognostic and Health Management (PHM) tool infrastructure using a model-based methodology for robotic systems. The main objective of this study is “Development of the General Prognostic and Health Management Tool” for ROS. The scope of this guide is processes and methodologies for conducting hazard rate of equipment, reliability predictions for electronic and mechanical systems. A comprehensive and systematic study of the different reliability models and analytical tools for various systems are also given. Furthermore, reliability, remaining useful life (RUL), and the probability of task completion of the robot (PoTC) will be estimated in this work. In this report, reliability and PoTC of the system is calculated by using hazard rate of the mechanical and electrical components, configuration of the robot (series, parallel, etc.). Results show that system reliability depends on hazard rate of all components in the system, their configurations, usage time and some enviromental conditions (temperature, load, humidity, etc.). PoTC is the task completion probability of the robot that depends on the calculated reliability and distance travelled along the task.

• **Parameters of PHM applications:** In the project, some parameters (sensor domains) required for PHM applications are given and failure rate formulas related to these parameters are found.

• **Model-based method development:** Accelerated life test functions and life distribution models required for the model-based method were obtained. Thus, by selecting the appropriate model, the reliability of the system with known failure rate will be obtained (See Section 4).

• **Hazard rate calculation algorithm:** The algorithm for calculating the failure rates of all electronic and mechanical components on the robot is obtained. In this way, how many failures each component will make can be calculated (See Section 5).

• **Reliability estimation algorithm development:** The reliability of the components in the system will be calculated according to the configuration with the help of failure rates. In addition, system reliability will be estimated using the failure rates (See Section 3 & Section 4).

• **Robot configuration setup:** Reliability calculation formulas have been obtained according to the configuration (series, parallel, hybrid, etc.) of the robot sub-systems, components and parts (See Section 3). By selecting the appropriate configuration for the robot, the reliability of the system will be obtained.

• **Robot task completion algorithm:** Probability of task completion of the mobile robot is obtained by using reliability of the system and distance travelled by robot along the task (See Section 6).

In this report, you can find why we use reliability analysis and what is the importance of the prognostic-aware systems. In Section 2 basic reliability concepts and formulations are given. In Section 3 discussed the analysis required for reliability estimation. In Section 4, life distribution models and accelerated life test models are given. Section 5 provides hazard rate calculations for both mechanical and electronic equipments. In the Section 6, probability of task completion (PoTC) of the mobile robot during specified task is given. In the last section, use case scenario is studied and an example scenario about the predict hazard rate of mobile robot, reliability calculation and PoTC calculation of our robot is given. An analysis of how much of the project is promised is given the following paragraph.

1. INTRODUCTION

Engineering systems such as parts, components, devices, etc. are not perfect. The perfect system is ideally the absence of failures in a certain lifetime. This is practically and economically impossible. However, in the all engineering works, engineers try to predict or prevent/minimize failures in the system. To minimize failures in the engineering system, we must understand “why” and “how” failures occur **[1]**. Potential failures in a system are generally unknown which indicates that the predictions of the failures that may occur are probabilistic. Therefore, the reliability analysis is a probabilistic process. Reliability analysis of complex systems with electronic and mechanical components is crucial for improving performance, extending system life and determining the remaining useful life (RUL) of the system. With the developing technology, model based or data driven techniques are used for failure prediction and reliability analysis of complex systems such as robots. When analyzing the reliability of a system, first of all, the paths leading to the failure of the system should be defined, the probabilities of the failures should be determined and a prognositc health management (PHM) system should be established according to these probabilities.

1.1. Why we need to Reliability Analysis?

Reliability generally shows how successful a system is in performing its intended function. In order to increase the system performance, intensive studies are carried out on reliability models and analytical tools. It is true that the consequences of unreliability in engineering can be very costly and often tragic. In a changing world, reliability becomes more important to ensure that systems operate with high performance and gain functionality. Reliability engineering is applied in many fields such as defense industry, robotics industry, aerospace industry etc. The current generation of mobile robots have poor reliability. In order to design more reliable robots, we need analytical tools for predicting robot failure. The failure data presented in **[2]**, valuable in that they provide for analyzing the reliability of robot subsystems. For instance, 35% of robot failures were due to failure of the actuators or related components. Another 26% were failures of the computers or software. The power subsystem caused 13%, communications caused 12% and sensing caused 10% of failures. Need for reliability is used as a reason for the dismissal of new concepts and designs whose capabilities have never been tested or appropriately evaluated. So, by using reliability analysis, system performence will be increased and tragic results will be prevented. Two basic skills are required to effectively perform reliability engineering tasks: first, how the actions taken during product or service design and manufacturing improve reliability, and second, to understand the ability to work with reliability modeling and quantitative aspects of statistical analysis **[3]**.

1.2. Failure Types

Failure is the case when a whole or part of a system is not working. Failures are categorized according to the source of failure, physical and human categories. Robotic-based physical errors are divided into classes based on common systems in all robots. These are effector, sensor, control system, power and communication. The effectors are defined as any operating component (engine, wheel, etc.) and any connection to these components. The control system category includes the on-board computer, sensors, software, etc. Sensors are equipment on the robot which collects information from the environment. Communication is necessary for the robot to interact with other robots or systems. The power layer is the part where the energy required for the movement of the robot is provided. Human errors are divided into design and interaction subclasses. Each failure, regardless of physical or human, has two characteristics; repairability and impact. The severity of failure is evaluated based on the impact of the robot on the task or task. A terminal robot failure is a condition that terminates the robot's current task, and a non-terminal failure that results in a significant deterioration of the robot's ability to perform its task. The repairability of the failure is defined either by the area that can be repaired or not for the area. If a robot is able to repair it under appropriate environmental conditions with equipment that frequently accompanies the robot on site, it is considered repairable. All explanations are shown in the Figure 1 **[4]**.

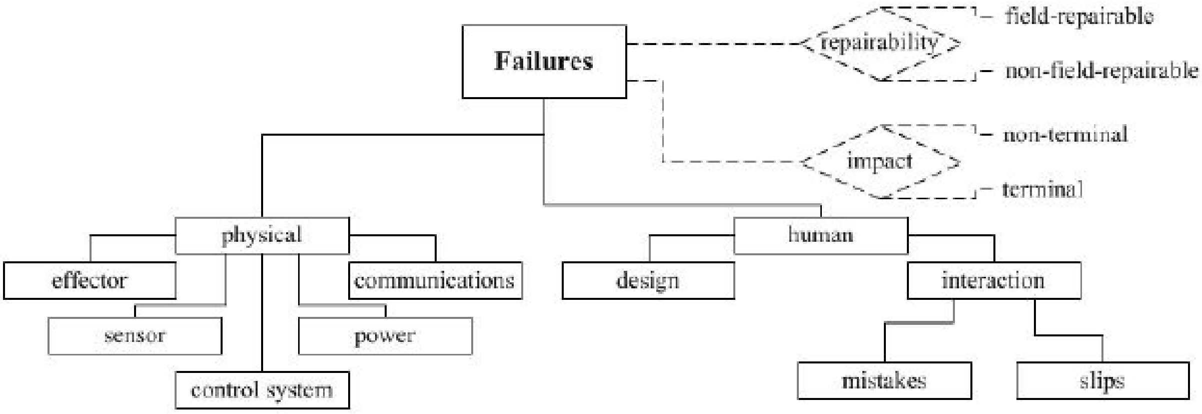

Figure 1: The taxonomy of mobile robot failures. Classes are shown with solid lines, and attributes with dashed lines.

1.3. Prognostic Health Management

A team of robots must be capable of knowing their health and making decisions about improving their reliability. Robotic systems are increasingly used in various fields. While it is important to realize autonomous behavior in the pioneering applications of robots, maintaining autonomy becomes more important with the use of robotic systems. Estimation of reliability is very important to suppress the possible errors of robotic systems and increase the success and health of robotic systems **[5]**.

Prognostic and Health Management (PHM) includes logistics, safety, reliability, mission criticality, and economic applicability. The PHM of the components or systems has both diagnostics and prognostic: Diagnosis is the process of detecting or isolating of faults, and prognostic is the prediction of the future situation or the remaining useful life (RUL) depending on the current situation and historical conditions. Prognostic is also based on failure of equipment after a breakdown period which can be used in the event of failure to prevent system failure and minimize operating costs. Concisely, diagnosis is related to the current state of any subsystem, and prognostic is related to the future state of the subsystem **[6]**.

Fault-tolerant control architectures have been developed for maintainability; however, they are genereally diagnostic-based. In contrast, prognostic-based strategies can predict risks before failure. The prognostic conscious system aims to integrate information about health and future working conditions into the process of selecting subsequent actions for the system. There are serious difficulties in dealing with prognostics. Prognostics deal with built-in data. The calculation cost of the internal diagnostics is limited in the robot, resulting in a limited number of sensors. These sensors generate thousands of signals or data streams while the robot is in motion. These signals are continuously sent to the main panel. It requires high storage capacity, resulting in high costs. Using this prognostic information, the system can make some kind of decision, such as replacing the component before failure, extending component life through load reduction or task switching, and optimally planning or re-planning a route. Some of the features a PHM system should have;

- Fault detection / isolation
- Advanced diagnosis
- Predictive prognostic
- Rule and failure time estimates
- Component lifecycle tracking
- Health reporting and information management
- Usage tracking.

2. BASIC RELIABILITY CONCEPTS

In this part, we start with define commonly used terms and metrics. After these definitions, mathematical backgrounds about the terms are given. Specifically we discuss, definition of reliability, relationship between reliability and failure rates, relationship between failure rates and MTTF, etc.

2.1. Terminology

Terminology list is created using references **[1]**, **[7], [8]** and **[9]**.

- *Reliability*: It refers to the probbaility that a system will operate correctly at a given time. It takes a number between 0 and 1.
- *Failure:* The robot or equipment used with the robot can not operate normally. Also, the termination of the ability of an item to perform a required function.
- *Fault:* Anything that could cause the system go into an error state.
- *Error:* A condition that may cause a malfunction in the system.
- *Hazard rate h(t):* It is the instantaneous failure rate at a given time.
- *Field-repairable failure:* A malfunction that can be repaired by a trained operator under appropriate environmental conditions, with equipment commonly accompanying the robot to the field.
- *Nonfield-repairable failure:* A failure that is not field-repairable.
- *Terminal failure:* A failure that terminates the robot's current task.
- *Nonterminal failure:* A failure that results in a noticeable deterioration in the robot's capability to perform its task.
- *Availability:* The probability that a system will be error-free at a given time.
- *Mean time between failures (MTBF)*: The expactation of the operating time between failures. It is an actually measure used for items repaired after a failure.
- *MTTF(Mean Time to Failure):* It is the expected value of the reliability. MTTF is a measure used for non-repairable items.
- *Maintainability:* It is the probaiblity of isolating and repairing a failure in a system over a period of time.
- *Useful life:* The length of time a product operates within a tolerable level of failure rate.
- *Mission time:* The time during which the item is carrying out task assigned to it.
- *L_x life:* Time until a specified percent of a device population will have experienced a failure (For example, L_{60} means the time duration when 60% of a device's population will have experienced a failure).

2.2. Formulations

Reliability is the probability of the system performing its intended function under the specified operating conditions for a specified period of time. Mathematically, the reliability function R(t) is the probability that a system will work successfully without failure in time intervals between 0 and t **[10]**.

$$R(t) = P(T > t), t \geq 0 \qquad (2\text{-}2\text{-}1)$$

where T is random variable representing the failure the probability that a failure was caused by a component type c is simply in Equation (2-2-2)**.**

$$P(failure) = \frac{Number\ of\ Failures\ Caused\ by\ c}{Total\ Number\ of\ Failures} \qquad (2\text{-}2\text{-}2)$$

Reliability and failure are related as;

$$R(t) = 1 - F(t) = P(T \leq t) \qquad (2\text{-}2\text{-}3)$$

where *R(t)* is the *reliability function*, and *F(t)* is the *unreliability function*.

The failure rate function (hazard function), is very important, because it specifies the rate of the system aging and also shows rate of change over the life of a component. Failure rate function is given in equation (2-2-4)

$$\lambda(t) = \frac{R(t)-R(t+\Delta_t)}{\Delta_t R(t)} = \frac{f(t)}{R(t)} \qquad (2\text{-}2\text{-}4)$$

where, $\lambda(t)dt$ indicates the probability that a device with age t will fail at small interval from time t + dt.

If the hazard rate function follows an exponential distribution with parameter λ, the hazard rate function;

$$\lambda\ (t) = \lambda \qquad (2\text{-}2\text{-}5)$$

This means that the hazard rate function of the exponential distribution is constant which means the system does not have an aging property. The reliability function and the hazard rate are related as (if lifetime distribution function is exponential with parameter λ);

$$R(t) = e^{-\int_0^t h(x)\times dx} = e^{-\lambda t} \qquad (2\text{-}2\text{-}6)$$

MTTF is the expected value of the reliability and related formulas about relability, failure rate and MTTF are given in Equation (2-2-7), Equation (2-2-8) and Equation (2-2-9) respectively.

$$MTTF = \int_0^{\infty} R(t) \times dt \qquad (2\text{-}2\text{-}7)$$

$$MTTF = \frac{1}{\lambda} \qquad (2\text{-}2\text{-}8)$$

2.3. Bathub Curve

Reliability models are descriptions of how the hazard rate changes over time. For most electronic and mechanical devices, when the hazard rate is plotted as a function of time, the resulting curve is similar to Figure 2 **[9]**. In this figure, vertical axis is the hazard rate, and the horizontal axis is time. The characteristic shape of this curve called as bathub curve and it has three distinct regions. On the left side of the curve, the hazard rate decreases over time and it is called *burn-in* or *infant mortality* period. This corresponds to the period in which the items fail largely due to defects in the material. Some failure sources at this phase are poor processes, poor quality control, poor debugging, etc. In the middle section there is a period of approximately constant hazard rate dominated by random failures and it is called *service life* or *useful life*. Some failure sources at this phase are, undetectable defects, human errors, higher random stress than expected, etc. On the right of the figure, the hazard rate increases over time and it is called *wearout* phase. During this period, components have reached the end of their useful life and began to deteriorate due to degradation. Some failure sources at this phase are, poor maintenance, incorrect overhaul practices, corrosion and creep, aging, etc. **[7]**.

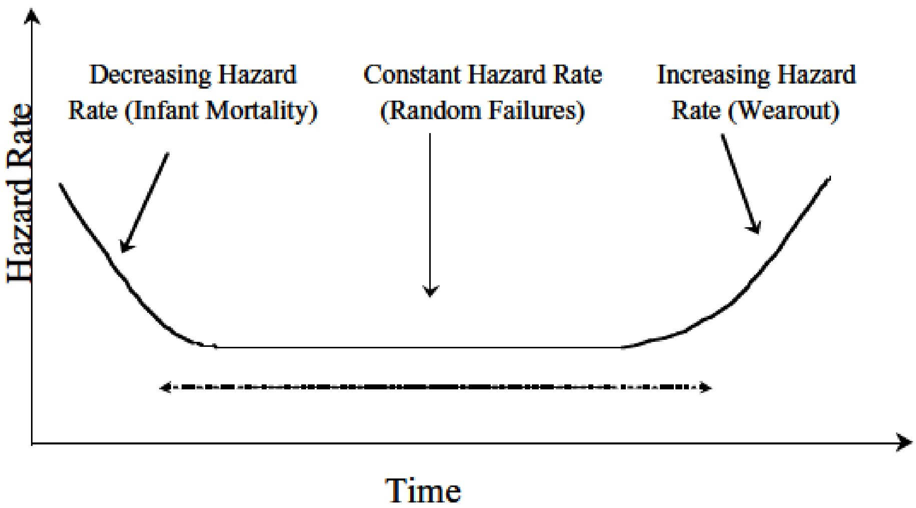

Figure 2: Bathub Curve

The bathtub rate curve shown in figure above can be represented by mathematically as **[11]**:

$$\lambda_t = \theta\lambda\beta t^{\beta-1} + (1-\theta)bt^{b-1}\alpha e^{\alpha t^b} \qquad (2\text{-}3\text{-}1)$$

For β, b,λ and $\alpha > 0$; $0 \leq \theta \leq 1$; $\beta = 0.5$, b= 1 and$t \geq 0$ and where t is time $\lambda(t)$ is the hazard rate or time t dependent failure rate, α and λ are the scale parameters and β and b are the shape parameters.

3. RELIABILITY ESTIMATION ALGORITHM

Over the years, reliability researchers working and developed various reliability assessment methods and techniques. Some examples of these methods and techniques are reliability block diagram, network diagram, fault tree analysis (FTA), failure modes and effective analysis (FMEA), hazard rate and operability (HAZOP), etc. The implementation of these methods and techniques depends on factors such as the specific need, the tendency of the systems, etc.

The most commonly used techniques in systems are reliability block diagrams. Reliability block diagrams which usually corresponds to the pyhsical arrangement of items in the system. It is often used to model the impact of item failures on system performance. The major advantage of using the reliability block diagram approach is the ease of reliability expression and evaluation. In this section, only reliability block diagrams are explained. Using hazard rates of components, usage time of components and configuration (series, parallel or hybrid) of system we may estimate reliability of robots. General information about the reliability block diagram representation is taken from references **[1]** and **[9]**.

3.1. Series System

A reliability block diagram is in a series configuration when the failure of any block results in a system failure. Accordingly, for the functional success of a series system, all blocks must operate successfully during the intended task period of the system. Figure 3 shows N series reliability block diagram.

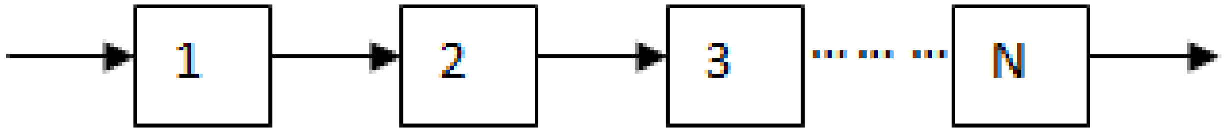

Figure 3: Series system reliability block diagram

System reliability $R_s(t)$;

$$R_s(t) = R_1(t) \times R_2(t) \ldots \times R_N(t) = \prod_{i=1} R_i(t) \qquad (3\text{-}1\text{-}1)$$

where $R_i(t)$ represents the reliability of the ith block.

3.2. Parallel System

In a parallel configuration, only failure of all blocks results give system failure. Accordingly, the success of only one block will be sufficient to guarantee the success of the system. Figure 4 shows N block parallel system block diagram.

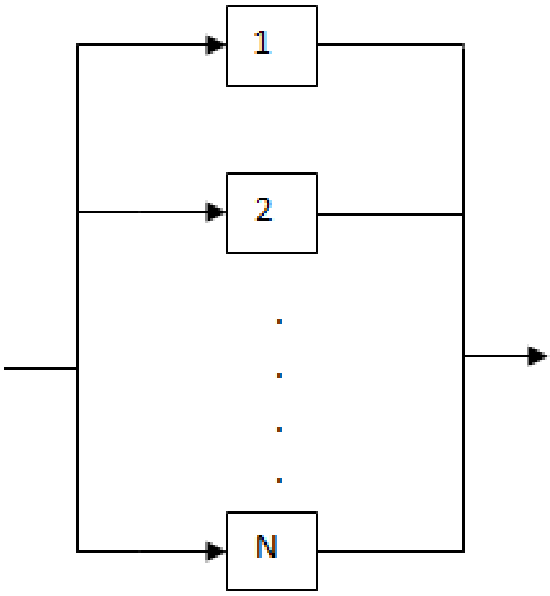

Figure 4: Parallel system block diagram

For a set of N independent blocks;

$$F_s(t) = F_1(t) \times F_2(t) \ldots \times F_N(t) = \prod_{i=1}^{N} F_i \quad (3\text{-}2\text{-}1)$$

Since Equation (2-2-3)

$$R_i(t) = 1 - \prod_{i=1}^{N} F_i \quad (3\text{-}2\text{-}2)$$

3.3. Hybrid System

Most practical systems are neither parallel nor series. Hybrid systems which are combination of the parallel and series configurations. Hybrid systems can be analyzed by dividing it into basic parallel and series sub-systems and then determining the reliability function for each sub-systems separately. The process continue until a reliability function is specified for the entire system. Figure 5 shows hybrid system block diagram example.

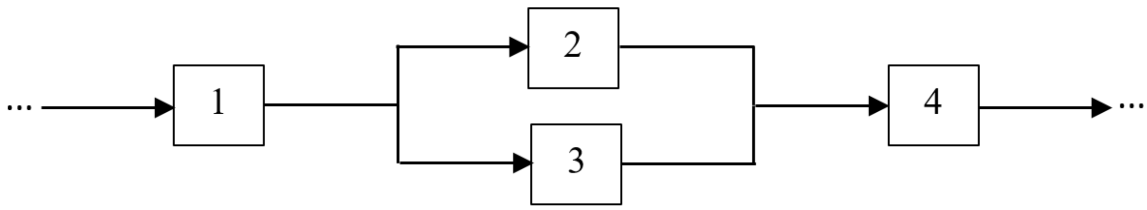

Figure 5: Hybrid System

To calculate the reliability of the system, firstly, calculate the reliability of the blocks 2 and 3 as parallel, then reliability of the system is calculated by using this calculated parallel results, block 1 and 4 as series.

3.4. Complex Nonparallel-Series System

In some systems, neither the parallel nor the series is called a non-parallel series system. The *decomposition method* is based on the concept of conditional probability for the decomposition of the this type of systems. Figure 6 shows complex nonparallel-series system example.

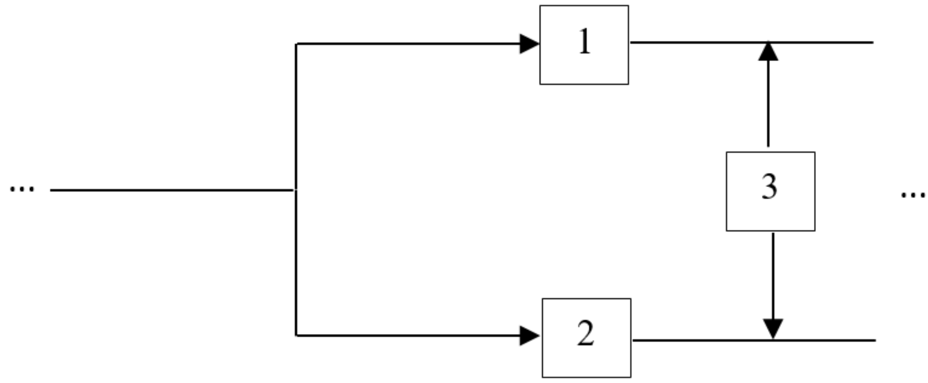

Figure 6: Complex nonparallel-series system

Analyzing this block diagram using Equation (3-4-1)

$$R_s(t) = R_s(t|\, unit\ 3\ working) * R_3(t) + R_s(t|\, unit\ 3\ failed) * \left(1 - R_3(t)\right) \quad (3\text{-}4\text{-}1)$$

Where, $R_s(t)$ indicates reliability of the system.

3.5. Standby Redundant System

A standby system includes an active unit and one or more inactive units. In the general, there will be N number of units with (N-1) of them in standby. For simplicity, consider a situation in which only one unit is active and others are standby, as shown in Figure 7. In the system given in Figure 7, the unit 1 operates continuously until it fails. The switching device detects a unit failure in the system and switches to another unit. This process continues until all standby units fail, in which case the system is considered failed.

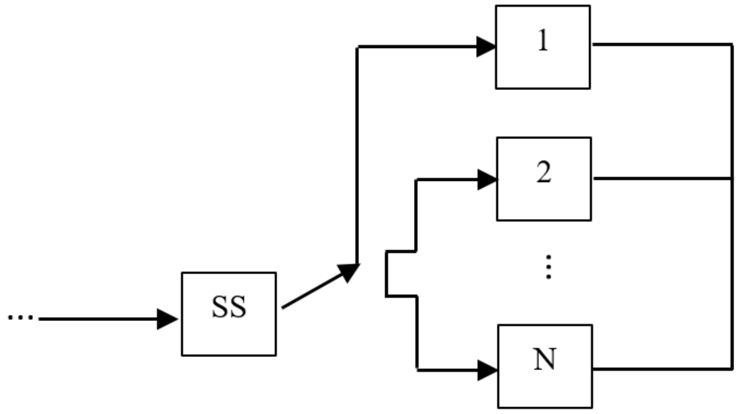

Figure 7: Standby Redundant System

When the active and the standby units have equal constant failure rates, λ, and the switching and sensing units are perfect, $\lambda_{sw} = 0$, the reliability function for such a system is:

$$R(t) = e^{-\lambda t} * (1 + \lambda * t) \quad (3\text{-}5\text{-}1)$$

3.6. k out of n Systems - (k,n) Systems

Some systems, or modules, are constructed of n active parallel components, but in order that the system function it is necessary that at least k out of the n units function. The reliability block diagram for the (k, n) system is the same as the parallel system and it is shown at Figure 8, but at least k items need to be operating for the system to be functional.

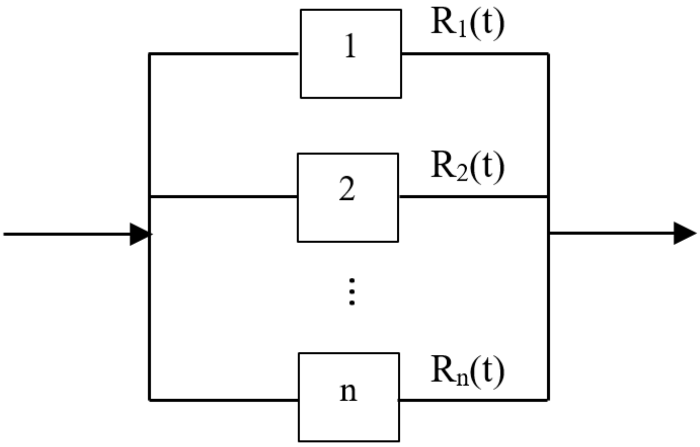

Figure 8: k out of n Systems

The reliability of this system, in which all components have same reliability R and independent form each other is;

$$R_{(k,n)}(t) = \sum_{j=k}^{n} \binom{n}{j} R^j (1-R)^{n-j} \qquad (3\text{-}6\text{-}1)$$

4. MODEL-BASED METHOD

In this section, we discussed model-based methodology. In this section, most commonly used life distribution models are given to base to the reliability model. Also, accelerated life test (ALT) models given which is used in different conditions in order to calculate reliability analysis. Both sub-sections are used to calculate reliability of systems.

4.1. Life Distribution Models

In this section, most commonly used life distribution models for hazard rate calculation is given. At initially, it is useful to to look at some metric definitions that is given in Table 1 **[12]**.

Table 1: Some metric definitions

Metric	**Definition**
f(t), the probability density function	$P(a < t < b) = \int_a^b \ f(t)dt$, to evaluate the likelihood of a failure occuring in the interval (a,b)
F(t), the cumulative distribution function	$P(t < b) = \int_0^b \ f(t)dt$, to evaluate the likelihood of a failure occuring by time b.
R(t), the survival function	$P(t > b) = 1 - F(b) = \int_b^\infty \ f(t)dt$, to evaluate the likelihood of survival to time b.
λ (t), the hazard function or instantaneous failure rate	$\lambda(t) = \frac{f(t)}{R(t)}$

4.1.1. Exponential Distribution

It is most commonly used in reliability analysis. This distribution can be attributed to primarily simplicity (constant hazard rate model), which corresponds to a realistic situations. It is widely used in electronics and probabilistic modeling. Equations related with this distribution given below.

$$f(t) = \lambda exp\,(-\lambda t) \tag{4-1-1-1}$$

$$F(t) = 1 - exp\,(-\lambda t) \tag{4-1-1-2}$$

$$h(t) = \lambda \tag{4-1-1-3}$$

$$MTTF = \frac{1}{\lambda} \tag{4-1-1-4}$$

4.1.2. Weibull Distribution

All three regions of the bathub curve can be represented by Weibull distribution and it is commonly used in many basic components such as capacitors, relays, bearings, etc. Equations related with this distribution given below.

$$f(t) = \frac{\beta(t)^{\beta-1}}{\alpha^\beta} exp\,exp\left[-\left(\frac{1}{\alpha}\right)^\beta\right] \tag{4-1-2-1}$$

$$F(t) = 1 - exp\,exp\left[-\left(\frac{1}{\alpha}\right)^\beta\right] \tag{4-1-2-2}$$

$$h(t) = \frac{\beta}{\alpha} exp\,exp\,(\frac{1}{\alpha})^{\beta-1} \tag{4-1-2-3}$$

$$MTTF = \alpha\,\Gamma\left(\frac{1+\beta}{\beta}\right) \tag{4-1-2-4}$$

Features of Weibull distribution over a range of β values are given in Table 2 [**1**]:

Table 2: Features of Weibull distribution over a range of β values

β	**Featrues**
< 1.0	Decreasing failure-rate
1.0	Exponential (constant failure rate)
> 1.0	Increasing failure-rate
2.0	Rayleigh single peak (linearly increasing)
~3.5	Normal shape
> 10	Type I extreme value

4.1.3. Gamma Distribution

It is a generalization form of exponential distribution. When the format parameter a is an integer, the gamma distribution is known as the *Erlangian Distribution*. Examples of applications such as time between recalibration of an instrument requiring recalibration after k uses, time between maintenance of items requiring maintenance after k uses, etc. Equations related with this distribution given below.

$$f(t) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} t^{\alpha-1} \exp \exp \left(-\frac{1}{\beta}\right) \quad (4\text{-}1\text{-}3\text{-}1)$$

$$F(t) = \frac{\int_0^t \; y^{\alpha-1} \exp(-y/\beta) dy}{\beta^{\alpha}\Gamma(\alpha)} \quad (4\text{-}1\text{-}3\text{-}2)$$

$$h(t) = \frac{t^{\alpha-1} \exp\exp\left(-\frac{1}{\beta}\right)}{\beta^{\alpha}[\,\Gamma(\alpha) - \int_0^t \; y^{\alpha-1} \exp(-y/\beta) dy} \quad (4\text{-}1\text{-}3\text{-}3)$$

$$MTTF = \beta\alpha \quad (4\text{-}1\text{-}3\text{-}4)$$

4.1.4. Normal Distribution

It is the basic distribution of the statistics. It can be used high-stress components, stress-strength analysis, tolerance analysis, etc. Equations related with this distribution given below.

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} \exp \exp \left(-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2\right) \quad (4\text{-}1\text{-}4\text{-}1)$$

$$F(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^t \blacksquare \exp\left(-\frac{1}{2}\left(\frac{\theta-\mu}{\sigma^2}\right)^2\right) d\theta \quad (4\text{-}1\text{-}4\text{-}2)$$

$$h(t) = \frac{f(t)}{1-F(t)} \quad (4\text{-}1\text{-}4\text{-}3)$$

$$MTTF = \mu \quad (4\text{-}1\text{-}4\text{-}4)$$

4.1.5. Lognormal Distribution

This distribution widely used in probabilistic design and it is useful for modeling fatigue-related and stress-strength phenomena. This model is particularly appropriate for failure processes that are the result of many small multiplicative errors. Equations related with this distribution given below.

$$f(t) = \frac{1}{\sigma_1 r\sqrt{2\pi}} \exp \exp \left(-\frac{1}{2{\sigma_1}^2}(\ln \ln (t) \; - \mu)^2\right) \quad (4\text{-}1\text{-}5\text{-}1)$$

$$F(t) = \frac{1}{\sigma_1\sqrt{2\pi}} \int_0^t \blacksquare \frac{1}{\theta} \exp \exp \left(-\frac{1}{2}\frac{(\ln\ln(\theta) - \mu_1)^2}{{\sigma_1}^2}\right) d\theta \quad (4\text{-}1\text{-}5\text{-}2)$$

$$h(t) = \frac{f(t)}{1-F(t)} \quad (4\text{-}1\text{-}5\text{-}3)$$

$$MTTF = exp\ exp\ \left(\mu_1 * \frac{1}{2}{\sigma_1}^2\right) \quad (4\text{-}1\text{-}5\text{-}4)$$

4.1.6. Extreme Value Distributions

It can be considered in the framework of the Extreme Value Theory. It is generally used exclusively to model environmental or stress such as minimum rainfall, maximum load, etc. It can be also used, breakdown voltage of capacaitors, distribution of breaking of some components, etc. Equations related with this distribution given below.

$$f(t) = \frac{1}{\delta} exp\ [\frac{1}{\delta}(t-\lambda) - \frac{t-\lambda}{\delta})] \quad (4\text{-}1\text{-}6\text{-}1)$$

$$F(t) = 1 - exp\ exp\ \left[- exp\ exp\ \left(\frac{t-\lambda}{\delta}\right)\right] \quad (4\text{-}1\text{-}6\text{-}2)$$

$$h(t) = \frac{1}{\delta} exp\ exp\ \left[\frac{t-\lambda}{\delta}\right] \quad (4\text{-}1\text{-}6\text{-}3)$$

$$MTTF = \lambda - 0.57768 \quad (4\text{-}1\text{-}6\text{-}4)$$

4.2. Accelerated Life Test Models

Discussed reliability models in the previous section, in terms of failure time distribution and these models are not suitable for situations that effect reliability such as stress factors, environmental conditions (ambient temperature, vibration, mechanical load, etc.). In this section, we will focus on the Accelerated Life Test (ALT). The purpose of these tests are to verify the life-cycle reliability of the product within a short time and accelerate the damage accumulation rate for relevant wearout failure mechnaisms. These tests show the weaknesses of the system and provide increase the reliability. In order to detect weaknesses, applied step stress (temperature, load, etc.) by increasing the levels until a failure occurs to the system or components. To accomplish this, we must know, accelerated model, parameters of model and lifetime distribution. An accelerated life reliability model is defined as the relationship between the time distribution of a device to failure and stress factors such as load, cycle rate, temperature, voltage, etc. Accelerated life reliability models are based on the physics of failure ideas **[1]** and **[13]**.

The acceleration factor (AF) term, is defined as the ratio of the life under life-cycle conditions to that under the test conditions. This acceleration factor is needed to quantitatively extrapolate reliability metrics such as time-to-failure and hazard rates from the accelerated environment to the usage environment, with some reasonable degree of assurance. The acceleration factor depends on the hardware parameters, life-cycle stress conditions, accelerated stress test conditions, and the relevant failure mechanism **[12]**. The acceleration factors are evaluated for each step of a given test plan thanks to quantitative relationships (Arrehnius, Eyring, etc) **[14]**. Acceleration factor is calculated by using this definition [**12**]:

$$AF = \frac{cycles\ of\ usage\ per\ unit\ of\ time\ under\ accelerated\ cycling}{cycles\ of\ usage\ per\ unit\ of\ time\ under\ normal\ cycling} = \frac{life\ under\ normal\ operating\ conditions}{life\ under\ elevated\ stress\ levels} \quad (4\text{-}2\text{-}1)$$

New hazard rate is calculated by;

$$\lambda_i = \lambda_0 * AF \quad (4\text{-}2\text{-}2)$$

Where λ_i: $New\ hazard\ rate,\ \lambda_0: old\ hazard\ rate,\ AF: accelerated\ factor$

4.2.1. Arrhenius Model

It is used when the damage mechanism is temperature sensitive (especially for dielectrics, semiconductors, battery cells, etc.). It defines the life of the product τ:

$$\tau = Ae^{(\frac{E_a}{kT})} \quad (4\text{-}2\text{-}1\text{-}1)$$

A: positive constant, E_a: activation energy, k: Boltzman constant ($8.6171 \times 10^{-5}\ eV/K$), and T absolute temperature.

The Arrhenius acceleration factor between the lifetime τ_1 for a temperature T_1 and the lifetime τ_2 for a temperature T_2 is:

$$AF = \frac{\tau_1}{\tau_2} = e^{\frac{E_a}{k}(\frac{1}{T_1}-\frac{1}{T_2})} \quad (4\text{-}2\text{-}1\text{-}2)$$

Using an exponential lifetime distribution with an Arrhenius acceleration model for each step indexed by i the exponential distribution parameter λ_i calculated as;

$$\lambda_i = \lambda_0 e^{\left(-\frac{E_a}{k}\left(\frac{1}{T_i}-\frac{1}{T_0}\right)\right)} \quad (4\text{-}2\text{-}1\text{-}3)$$

Where T_i the temperature at step i, T_0 the temperature in nominal conditions, λ_0 the failure rate in nominal conditions, and E_a the activation energy.

4.2.2. Eyring Model

It is used to when the temperature and another variable(s) sensitive cases. The lifetime given as:

$$\tau = (\frac{A}{T})e^{(\frac{B}{kT})}e^{(V(C+\frac{D}{kT}))} \quad (4\text{-}2\text{-}2\text{-}1)$$

with V the stress as voltage, humidity, current density, etc., and A, B, C and D the test and failure specific constants.

Using an exponential lifetime distribution with an Eyring acceleration model for each step indexed by i the exponential distribution's parameter λ_i calculated for combined (temprature and voltage) step stress test as (with A = 0, B = B, C = C and D = 0)

$$\lambda_i = \lambda_0 e^{\left(\frac{B}{kT_i}\right)} e^{CV_i} \quad (4\text{-}2\text{-}2\text{-}2)$$

with T_i the temperature at step i, B and C the model parameters, V_i the voltage at step i, and λ_0 the failure rate in nominal conditions.

4.2.3. Inverse Power Model

It is used when the damaging stress is sensitive to a particular stress (e.g., dielectrics, ball or roller bearing, mechanical components submitted to fatigue, etc.). The inverse power model defines the damaging rate under a constant stress V. The lifetime is given:

$$\tau = \frac{A}{V^\gamma} \quad (4\text{-}2\text{-}3\text{-}1)$$

with V the constant stress (for example temperature), and A and γ the test and failure specific constants. The acceleration factor between the lifetime τ_1 for a stress level V_1 and the lifetime τ_2 for a stress level V_2 is:

$$AF = \frac{\tau_1}{\tau_2} = (\frac{V_2}{V_1})^\gamma \quad (4\text{-}2\text{-}3\text{-}2)$$

4.2.4. Others

Coffin-Manson model is used for mechanical and electronic components. Coffin–Manson based law for thermal cycling fatigue found as **[15]**:

$$AF = (\frac{\Delta T_2}{\Delta T_1})^2 (\frac{F_1}{F_2})^{0.33} \quad (4\text{-}2\text{-}4\text{-}1)$$

where, AF is the acceleration factor, ΔT_1 and ΔT_2 are the amplitude of thermal variations of use and stress respectively, F_1 and F_2 are the frequency of the usea nd stress cycles respectively.

Gunn's law for humidity **[15]**:

$$AF = e^{\beta(RH_2-RH_1)} \quad (4\text{-}2\text{-}4\text{-}2)$$

where, AF is the acceleration factor, $\beta = 0.08$, RH_1 and RH_2 are the humidity level of use and stress respectively.

5. HAZARD RATE CALCULATION ALGORITHMS

In this section, mechanical **[16-18]** and electrical hazard rate **[19]** models are given. This section is responsible for components hazard rate calculation. Both mechanical and electronical equipments are found here is the equipment found in our robot.

5.1. Mechanical Equipment Reliability

In this section, calculation of mechanical equipment's hazard rate is given. Most of the hazard rate calculations are taken from **[16]**.

5.1.1. Springs

A generalized failure rate equation of a compression spring calculated as:

$$\lambda_{SP} = \lambda_{SP,B} * C_G * C_{DW} * C_{DC} * C_N * C_Y * C_L * C_K * C_{CS} * C_R * C_M \quad (5\text{-}1\text{-}1\text{-}1)$$

where;

$\lambda_{SP,B}$ = Base failure rate for spring, *23.8 failures/million hours*

C_G = The effect of the material rigidity modulus on the base failure rate (See Table 3)

C_{DW} = The effect of the wire diameter on the base failure rate (See Equation 5-1-1-2)

C_{DC} = The effect of coil diameter on the base failure rate (See Equation 5-1-1-3)

C_N = The effect of the number of active coils on the base failure rate (See Equation 5-1-1-4)

C_Y = The effect of material tensile strength, T_s, on the base failure rate (See Table 4)

C_L = The effect of spring deflection on the base failure rate (See Equation 5-1-1-5)

C_K = The spring concentration factor on the base failure rate (See Equation 5-1-1-6)

C_{CS} = The effect of spring cycle rate on the base failure rate (See Equation 5-1-1-7, 5-1-1-8, 5-1-1-9)

C_R = The effect of a corrosive environment on the base failure rate (See *)

C_M = The effect of the manufacturing process on the base failure rate (See *)

Table 3: Moduli of Rigidity and Elasticity for Typical Spring Materials

MATERIAL	C_G	MATERIAL	C_G
<u>Ferrous:</u>		<u>Non-Ferrous:</u>	
Music Wire	1.08	Spring Brass	0.08
Hard Drawn Steel	1.00	Phosphor Bronze	0.14
Chrome Steel	0.92		0.23
Silicon-Manganese	0.83	Beryllium Copper	0.76
Stainless, 302, 304, 316	0.67		0.56
Stainless 17-7 PH	0.76	Inconel	
Stainless 420	0.88	Monel	
Stainless 431	0.97		

$$C_{DW} = \left(\frac{D_W}{0.085}\right)^3 \quad D_W\text{, wire diameter (inches)} \quad (5\text{-}1\text{-}1\text{-}2)$$

$$C_{DC} = \left(\frac{0.58}{D_C}\right)^6 \quad D_C\text{, coil diameter (inches)} \quad (5\text{-}1\text{-}1\text{-}3)$$

$$C_N = \left(\frac{14}{N_a}\right)^3 \quad \text{Na, number of active coils} \quad (5\text{-}1\text{-}1\text{-}4)$$

$$C_L = \left(\frac{L_1 - L_2}{1.07}\right)^3 \quad L_1\text{-}L_2 \text{ spring deflections (inches)} \quad (5\text{-}1\text{-}1\text{-}5)$$

Table 4: Material Tensile Strength Multiplying Factor, C_Y

MATERIAL	C_Y
Brass	5.15
Phosphor Bronze	3.51
Monel 400	2.25
Inconel 600	1.74
Monel K500	1.28
Copper-Beryllium	1.00
17-7 PH, RH 950	0.74
Hard Drawn Steel	0.68
Stainless Steel 302, 18-8	0.59
Spring Temper Steel	0.47
Chrome Silicon	0.36
Music Wire	0.27

$$C_K = \left(\frac{K_W}{1.219}\right)^3, K_W = \frac{4r-1}{4r+1} + \frac{0.616}{r} \text{ and } r = \frac{D_C}{D_W}, \text{ r spring index} \quad (5\text{-}1\text{-}1\text{-}6)$$

For CR ≤ 30 cycles/min, $C_{CS} = 0.1$ (5-1-1-7)

For 30 cycles/min < CR ≤ 300 cycles min, $C_{CS} = \frac{C_R}{300}$ (5-1-1-8)

For CR > 300 cycles/min, $C_{CS} = \left(\frac{C_R}{300}\right)^3$ (5-1-1-9)

where: CR = spring cycle rate, cycles/min

*C_R and C_M is used in conjunction with the base failure rate. Greater than 1 are used based on the previous user's experience.

5.1.2. Bearings

Equation (5-1-2-1) is used to determine the bearing failure rate.

$$\lambda_{BE} = \lambda_{BE,B} * C_Y * C_R * C_V * C_{CW} * C_t * C_{SF} * C_C \quad (5\text{-}1\text{-}2\text{-}1)$$

$\lambda_{BE,B}$ = Base failure rate, failures/million hours = $\frac{1}{L_{10\,h}}$ (5-1-2-2)

where $L_{10} = \frac{10^6}{60n}\left(\frac{L_S}{L_A}\right)^y$ (5-1-2-3)

y: constant 3 for ball bearings, 3.3 for roller bearings, L_S dynamic load rating of bearing, ıbf, L_A equivalent radial load on bearing, ıbf, L_{10} bearing life with reliability 90%, millions of revolutions, n operation speed, revolutions/min.

C_Y = Multiplying factor applied load (See Equation 5-1-2-4)

C_R = Life adjustment factor for reliability (See Equation 5-1-2-5)

C_V = Multiplying factor for lubricant (See Equation 5-1-2-6)

C_{CW} = Multiplying factor for water contaminant level (See Equation 5-1-2-7, 5-1-2-8)

C_t = Multiplying factor for operating temperature (See Equation 5-1-2-9, 5-1-2-10)

C_{SF} = Multiplying factor for operating service conditions (See Table 5)

C_C = Multiplying factor for lubrication contamination level (See Table 6)

$$C_y = (\frac{L_A}{L_S})^y \quad (5\text{-}1\text{-}2\text{-}4)$$

$$C_R = \frac{0.223}{\left(ln\left(\frac{100}{R}\right)\right)^{2/3}} \quad (5\text{-}1\text{-}2\text{-}5)$$

$C_V = (\frac{V_o}{V_L})^{0.54}$, V_o = Viscosity of specification fluid V_L = Viscosity of lubricant used (5-1-2-6)

For CW ≤ 0.8, $C_{CW} = 1.0 + 25.50CW - 16.25\,CW^2$ (5-1-2-7)

For CW > 0.8, $C_{CW} = 11.00$ (5-1-2-8)

where: CW = Percentage of water in the lubricant

$C_t = 1.0$ for $T_0 < 183$°C (5-1-2-9)

$C_t = \left(\frac{T_0}{183}\right)^3$ for $T_0 \geq 183$°C (5-1-2-10)

where: T_0 = operating temperature of the bearing

Table 5: Bearing Service Factors

Type of Application	**Service Factor, C_{SF}**	
	Ball Bearing	**Roller Bearing**
Uniform and steady load, free fromshock	1.0	1.0
Normal operation, light shock load	1.5	1.0
Moderate shock load	2.0	1.3
Heavy shock load	2.5	1.7
Extreme and indeterminate shock load	3.0	2.0
Precision gearing	1.2	
Commercial gearing	1.3	
Toothed belts		1.2
Vee belts		1.8
Flat belts		3.0

Table 6: Bearing Contamination Level

Type of Application	**Service Factor, C_C**	
	Bearing diameter < **100 mm**	**Bearing diameter** > **100 mm**
Extreme cleanliness- particle sizeapprox. lubricant film thickness(laboratory conditions)	1.0	1.0
High cleanliness – oil filtered throughfine filter ≤ 10 micron	1.4	1.2
Normal cleanliness – slightcontamination in lubricant	1.8	1.4
Slight contamination –slightcontamination in lubricant – hardparticles > 10 micron	2.5	2.0

Severe contamination – course filtering,no integral seals	5.0	3.3

5.1.3. Gears

The gear failure rate can be expressed as:

$$\lambda_G = \lambda_{G,B} * C_{GS} * C_{GP} * C_{GA} * C_{GL} * C_{GT} * C_{GV} \quad (5\text{-}1\text{-}3\text{-}1)$$

Where:

$\lambda_{G,B}$ = Base failure rate of gear, failures/million operating hours (See Equation 5-1-3-2)

C_{GS} = Speed deviation with respect to design (See Equation 5-1-3-3)

C_{GP} = Actual gear loading with respect to design (See Equation 5-1-3-4)

C_{GA} = Misalignment (See Equation 5-1-3-5)

C_{GL} = Lubrication deviation with respect to design (See Equation 5-1-3-6)

C_{GT} = The operating temperature (See Equation 5-1-3-7 and 5-1-3-8)

C_{GV} = The AGMA Service Factor (See Table 7)

$$\lambda_{G,B} = RPM * 60 * \frac{1}{design\ life(revolutions)} \quad (5\text{-}1\text{-}3\text{-}2)$$

$$C_{GS} = k + (\frac{V_o}{V_d})^{0.7} \quad (5\text{-}1\text{-}3\text{-}3)$$

k constant(1.0), V_o= Operating Speed, RPM, V_d= Design Speed, RPM

$$C_{GP} = (\frac{L_o/L_d}{k})^{4.69} \quad (5\text{-}1\text{-}3\text{-}4)$$

k = Constant, 0.50, L_o= Operating Load, lbs, L_d= Design Load, lbs

$$C_{GA} = (\frac{A_E}{0.006})^{2.36} \text{ , } A_E = \text{Misalignment angle in radians} \quad (5\text{-}1\text{-}3\text{-}5)$$

$$C_{GL} = k + (\frac{V_o}{V_L})^{0.54} \quad (5\text{-}1\text{-}3\text{-}6)$$

where: V_o= Viscosity of specification lubricant, lb-min/in2, V_L= Viscosity of lubricant used, lb-min/in2

$$C_{GT} = \frac{460+T_{AT}}{620}\text{, for } T_{AT} > 160\ °F \quad (5\text{-}1\text{-}3\text{-}7)$$

$$C_{GT} = 1\text{, for } T_{AT} <= 160\ °F \quad (5\text{-}1\text{-}3\text{-}8)$$

T_{AT}= Operating temperature, °F

Table 7: Typical AGMA Service Factor, C_{GV}

Prime Mover	Character of Load on Driven Member		
	Uniform	**Medium Shock**	**Heavy Shock**
Uniform	1.00	1.25	1.75
Medium Shock	1.25	1.50	2.00
Heavy Shock	1.50	1.75	2.25

5.1.4. Actuators

The complete failure rate model for the piston/cylinder actuator can be expressed as follows:

$$\lambda_{AC} = \lambda_{AC,B} * C_{CP} * C_T \quad (5\text{-}1\text{-}4\text{-}1)$$

where:

$\lambda_{AC,B}$ = Base failure rate of actuator, failures/million cycles (See Equation 5-1-4-2)

C_{CP} = Contaminant multiplying factor (See Equation 5-1-4-4)

C_T = Temperature multiplying factor (See Equation 5-1-4-5)

$$\lambda_{AC,B} = \frac{10^6}{N_o} \qquad (5\text{-}1\text{-}4\text{-}2)$$

where: N_o = Number of cycles in constant wear phase (See Equation 5-1-4-3)

$$N_o = k_2 \left(\frac{\gamma F_y}{\left(\frac{W_A \left(\frac{D_1 - D_2}{D_1 D_2} \right)^2}{\left(\frac{1-\eta_1{}^2}{E_1} - \frac{1-\eta_2{}^2}{E_2} \right)^2} \right)^{1/3}} \right)^9 \qquad (5\text{-}1\text{-}4\text{-}3)$$

where:

γ = Wear factor * (The wear factor, γ, will be equal to 0.20 for materials that have a high susceptibility to adhesive wear, in which the wear process involves a transfer of material from one surface to the other. The wear factor will be equal to 0.54 for materials that have little tendency to transfer material in which the material is subject to micro-gougingof the surfaces by the asperities on the material surface.)

$k_2 = 17.7 * 10^3$ which includes a lubrication constant

F_y = Yield strength of softer material, lbs/in2 (See Table 8)

D_1 = Diameter of cylinder, in; D_2 = Diameter of piston, in

η_1 = Poisson's ratio, cylinder; η_2 = Poisson's ratio, piston

E_1 = Modulus of elasticity, cylinder, lbs/in^2; E_2 = Modulus of elasticity, piston, lbs/in^2

W_A = Axial Load on the actuator, lbf

Table 8: Values of Yield Strength for Various Metals

Metal	**Yield strength, ksi**
Ordinary structural steel	30 - 40
Low alloy, high strength steel	40 - 80
Heat treated steel casting	40 - 120
Cold rolled steel	70 - 85
Stainless steel	50 - 80
Heat treated wrought aluminum	10 - 50
Aluminum alloy	35 - 42
Pure rolled aluminum	5 - 21
Cast aluminum	15 - 25
Wrought iron	25 - 35
Cast iron	8 - 40
Magnesium alloy	11 - 30

The contaminant multiplying factor can be established as follows:

$$C_{CP} = C_H * C_S * C_N \qquad (5\text{-}1\text{-}4\text{-}4)$$

where:

C_H = Particle hardness multiplying factor = $\frac{H_P}{H_C}$

H_P = Piston Hardness (See Table 9)

H_C = Cylinder Hardness (See Table 9)

C_S = Filtration multiplying factor = Filter size (micron) / 10

C_N = Particle size multiplying factor - For most applications the particle size factor will be equal to approximately 1.0. For severe conditions where the number of contaminants and particle size can be expected to increase, the particle size factor may be expected to approach a value of 2.0.

Table 9: Material Hardness (Use ratio of hardest particle/piston hardness for C_H)

Material	**Hardness($H_V * 10^6$)**
Plain carbon steels	
- Low strength steel	140
- High strength steel	220
Low-alloy Steels	
- 4320	640
- 4340	560
Stainless Steels	
- 303	170
- 304	160
- 631 (17-7 PH hardened)	520
- 631 (17-7 PH annealed)	170
- Austenitic AISI 201 annealed)	210
- Martensitic 440C (hardened)	635
- 630 (17-4 PH hardened)	470
Nickel Alloys	
- 201	100
Nickel-copper Alloys	
- Monel (annealed)	120
- Monel K-500 (annealed)	162
Ni-Cr-Mo-Fe Alloys	
- Inconnel 625	140
- Hastelloy	200
Aluminum	
- AISI 1100 (annealed)	25
- AISI 1100 (cold worked)	45
- AISI 2024 (annealed)	50
- AISI 2024 T4 (heat treated)	125
- AISI 6061 (annealed)	32
- AISI 6061 T6 (heat treated)	100

$$C_T = e^{\frac{\theta}{T_a}\left(1-\frac{T_a}{T}\right)} \tag{5-1-4-5}$$

where:

T_a = Ambient temperature, 25.2 ℃

T = Operating temperature, ℃

It is noted that the ratio $\frac{\theta}{T_a}$ is in the range between 4.0 and 20.0.

θ = Activation energy constant, K

T = Operating temperature, K

Values for the parameter θ are in the range between 1200 K and 6000 K.

5.1.5. Electric Motors

The total motor system failure rate is the sum of the failure rates of each of the parts in the motor:

$$\lambda_M = (\lambda_{M,B} * C_{SF}) + \lambda_{WI} + \lambda_{BS} + \lambda_{ST} + \lambda_{AS} + \lambda_{BE} + \lambda_{GR} + \lambda_C \quad (5\text{-}1\text{-}5\text{-}1)$$

where:

$\lambda_{M,B}$ = Base failure rate of motor, failures/million hours (See Table 10)

C_{SF} = Motor load service factor (See Table 11)

λ_{WI} = Failure rate of electric motor windings, failures/million hours (See Equation 5-1-5-2)

λ_{BS} = Failure rate of brushes, *3.2 failures/million hours/brush* (See Reference **17**)

λ_{ST} = Failure rate of the stator housing, *0.001 failures/million hours* (See Reference **17**)

λ_{AS} = Failure rate of the armature shaft, failures/million hours (See Section 5.1.9)

λ_{BE} = Failure rate of bearings, failures/million hours (See Section 5.1.2)

λ_{GR} = Failure rate of gears, failures/million hours (See Section 5.1.3)

λ_C = Failure rate of capacitor (if applicable) (See Reference **19**)

Table 10: Base Failure Rate of Motor, $\lambda_{M,B}$

Type of Motor	$\lambda_{M,B}$ **(failures/million hours)**
DC	2.17
DC brushless	1.75
AC single phase	6.90
AC polyphase	10.00

Table 11: Motor Load Service Factor, C_{SF}

Load Type	**Load Description**	C_{SF}
Uniform Load	One way continuous operation, minimal load fluctuation, no shock or vibration	1.00
Light Impact	Frequent starting and stopping, stepping motor operation, minimal shock and vibration	1.50
Medium Impact	Frequent bidirectional, reversible motor operation, moderate load impact, shock and vibration	2.00
Heavy Impact	Subject to heavy vibration, shock loads, heavy load fluctuations	3.00

$$\lambda_{WI} = \lambda_{WI,B} * C_T * C_V * C_{alt} \quad (5\text{-}1\text{-}5\text{-}2)$$

where:

$\lambda_{WI,B}$ = Base failure rate of the electric motor windings, failures/million hours (See Equation 5-1-5-3)

C_T = Multiplying factor which considers the effects of ambient temperature on the base failure rate (See Equation 5-1-5-4 and Table 12)

C_V = Multiplying factor which considers the effects of electrical source voltage variations (See Equation 5-1-5-5 and 5-1-5-6)

C_{alt} = Multiplying factor which considers the effects of operation athigh altitudes (See Equation 5-1-5-7 and 5-1-5-8)

$$\lambda_{WI,B} = \frac{1.0*10^6}{L_I} \tag{5-1-5-3}$$

where:

L_I = Expected winding life, hours (If a manufacturer's winding life is not available, a winding life of 25,000 hours (failure rate $\lambda_{WI,B}$ = *40.0 failures/million hours*) can be expected from most manufacturers.

Table 12: Motor Insulation Ratings

Insulation Class	Temperature Rating *	Assumed Ambient Temperature **	Allowable Temperature Rise	Hot Spot Allowance
A	105 °C	40 °C	60 °C	5 °C
B	130 °C	40 °C	85 °C	5 °C
F	155 °C	40 °C	110 °C	5 °C
H	180 °C	40 °C	135 °C	5 °C

* Maximum operating temperature allowed which includes ambient temperature, allowable temperature rise and a hot spot allowance. Manufacturers may use a mixture of materials in their motors providing a higher allowable temperature than the listed temperature rating for the insulation which permits a higher allowable ambient temperature. Refer to manufacturer’s specification if in doubt.

** After adding the ambient temperature + temperature rise + hot spot temperature, any difference between this sum and temperature rating can be applied to ambient temperature.

$$C_T = 2^{\frac{T_0-40}{10}} \tag{5-1-5-4}$$

where: T_0= Ambient temperature surrounding motor with motor running atexpected full load conditions, °C.

For single phase motors:

$$C_V = 2^{10\frac{V_D}{V_R}} \tag{5-1-5-5}$$

where V_D = Difference between rated and actual voltage and V_R = Rated voltage

For three phase motors:

$$C_V = 1 + (0.40V_U)^{2.5} \tag{5-1-5-6}$$

where:

$V_U = \%\ voltage\ unbalance = 100 * \frac{greatest\ voltage\ difference}{average\ phase\ voltage}$ And: V_U = 0% to 3%

For operating altitudes > 3300 feet:

$$C_{alt} = 1.00 + 8 * 10^{-5}(a - 3300\,ft) \tag{5-1-5-7}$$

For altitudes ≤ 3300 ft, $C_{alt} = 1.0$ (5-1-5-8)

where a = Operating altitude in feet

5.1.6. Threaded Fasteners

Equation (5-1-6-1) provides a determination of an expected failure rate of a threaded fastener in hours of operation.

$$\lambda_F = \lambda_{F,B} * C_{SZ} * C_L * C_T * C_I * C_K \qquad (5\text{-}1\text{-}6\text{-}1)$$

Where:

λ_F = Failure rate of fastener, failures/million hours

$\lambda_{F,B}$ = Base failure rate, failures/failures/million hours. (See Table 13)

C_{SZ} = The effects of size deviation from the S-N test specimen (See Equation 5-1-6-2 and 5-1-6-3)

C_L= The effects of different loading applications (See Table 14)

C_T = Elevated temperature multiplying factor (See Equation 5-1-6-4 and 5-1-6-5)

C_I = The severity of in-service cyclic shock (impact) loading (See Table 15)

C_K = Stress concentration multiplying factor for fastener threads (See Table 16)

Table 13: Fastener Base Failure Rate

Grade / Class	Diameter, Inches	Proof Load, kpsi	Base Failure Rate, Failures/million hours
SAE 1	¼-1 ½	33	0.260
SAE 2	¼ - ¾	55	0.156
SAE 2	¾ - 1 ½	33	0.260
SAE 4	¼ - 1 ½	65	0.132
SAE 5	¼ - 1	85	0.101
SAE 5	1 – 1 ½	74	0.116
SAE 5	1 ½ -3	55	0.156
SAE 7	¼ -1 ½	105	0.082
SAE 8	¼ -1 ½	120	0.072
ISO 4.6	-- to 1 ½	33	0.260
ISO 5.8	-- to 1 ½	55	0.156
ISO 8.8	-- to 1 ½	85	0.101
ISO 10.9	-- to 1 ½	120	0.072
ASTM A325	½ - 1	85	0.101
ASTM A325	1 1/8 -1 ½	74	0.116
ASTM A354,BB	¼ -2 ½	80	0.107
ASTM A354,BB	2 ¾ -4	75	0.114
ASTM A354,BC	¼ -2 ½	105	0.082
ASTM A354,BC	2 ¾ -4	95	0.090
ASTM A354,BD	¼ -1 ½	120	0.072
ASTM A490	¼ -1 ½	120	0.072

For bending or torsional loading:

$$C_{SZ} = \left(\frac{0.370d}{0.3}\right)^{-0.1133} \quad (5\text{-}1\text{-}6\text{-}2)$$

where: d = Major diameter of fastener, 2 inches or less

For axial loading:

$$C_{SZ} = 1.0 \quad (5\text{-}1\text{-}6\text{-}3)$$

Table 14: Load Multiplying Factors

TYPE OF LOAD APPLIED	C_L
Axial (σT,ult ≤ 220 kpsi)	1.09
Axial (σT,ult > 220 kpsi)	1.00
Bending	1.00
Torsion and Shear	1.72

For steel operating above 160 °F

For T_0 > 160 °F : $C_T = \frac{460+T_0}{620}$ (5-1-6-4)

and:

For $T_0 \leq 160$ °F : $C_T = 1.0$ (5-1-6-5)

where: T_0 = Operating temperature of fastener, °F

Table 15: Multiplying Factor for Impact Loading

IMPACT CATEGORY	C_I	
	Normal Vibration	**Continuous High Vibration**
LIGHT (rotating machinery - motors, turbines, centrifugal pumps)	1.00	1.50
MEDIUM (rotary & reciprocating motion machines - compressors, pumps)	1.25	1.88
HEAVY (presses for tools & dies, shears)	1.67	2.50
VERY HEAVY (hammers, rolling mills, crushers)	2.50	3.75

Table 16: Multiplying Factor for Threaded Elements, C_K

SAE GRADE BOLT	C_K	
	ROLLED THREADS	**CUT THREADS**
0-2	2.2	2.8
4-8	3.0	3.8

5.1.7. Mechanical Couplings

Gear coupling unit failure rate is calculated as:

$$\lambda_{CP} = (\lambda_{CP,B} * C_{SF}) + \lambda_{GR} + \lambda_{SE} + \lambda_H \quad (5\text{-}1\text{-}7\text{-}1)$$

where:

$\lambda_{CP,B}$ = Failure rate of coupling, failures/million cycles A typical failure rate of a coupling from data sources is *5.0 failures per million cycles*.

C_{SF} = Service factor multiplying factor (See Table 17)

λ_{GR} = Failure rate of gears, failures/million cycles (See Section 5.1.3)

λ_{SE} = Failure rate of seals, failures/million cycles (See Reference **16**)

λ_{H} = Failure rate of coupling housing including hubs, failures/million cycles. The failure rate can be estimated at *0.001 failures/million cycles*.

Table 17: Service Factors for a Mechanical Coupling

Driven Machinery	Normal Torque Characteristic	High or Non-uniform Torque
Uniform	1.1	1.2
Light shock	1.2	1.3
Medium shock	1.3	1.4
Heavy shock	1.4	1.5

5.1.8. Sensors & Transducers

A sensor is a hardware device that measures a physical quantity and produces a signal which can be read by an observer or by an instrument.

Table 18: Typical Sensor Applications

Sensor Classification	Typical Sensor/Transducer
Thermal	Thermostat, thermister, thermocouple, thermopile
Force	Mechanical force, strain gauge, torque
Positional	Potentiometer, LVDT, rotary encoder
Fluid	Pressure, flow, viscometer
Optical	Photodiode, phototransistor, photodetector, infrared,fiberoptic
Motion	Displacement, velocity, acceleration, vibration, shock
Presence	Proximity
Environmental	Temperature, altitude, humidity, smoke

A reliability model of the overall sensor network can be written as follows:

$$\lambda_{TD} = \lambda_{TD,B} + \lambda_S + \lambda_T + \lambda_C + \lambda_P + \cdots + \lambda_X \qquad (5\text{-}1\text{-}8\text{-}1)$$

where:

$\lambda_{TD,B}$ = Base failure rate of sensor, failures/million hours

λ_S = Failure rate of sensing element (See Table 19)

λ_T = Failure rate of the transmission line (See Reference **19**)

λ_C = Failure rate of the computational device (See Reference **19**)

λ_P = Failure rate of the power source (See Reference **19**)

λ_X = Failure rate of other components comprising the sensor or sensor network

Table 19: Typical Failure Rates for Sensing Elements

Sensor Transducer Classification	**Sensor Transducer**	**Technology**	**Failure Rate λ_S**
Thermal	RTD	Resistive	1.50
	Thermistor	Semiconductor	3.50
	Thermocouple	Thermoelectric	5.00
	Infrared	Emissivity	7.50
	Thermostat	Bimetallic	20.00
Mechanical Force/Pressure	Force transducer	Semiconductor	4.00
	Strain gauge	Resistive	7.50
	Strain gauge	Semiconductor	23.00
	Torque transducer	Magnetic	4.50
	Load cell	Strain gauge	23.00
Fluid	Fluid pressure sensor	Piezoelectric	13.00
	Fluid flow sensor	Resistive	14.30
	Fluid flow sensor	Capacitance	10.70
	Air flow sensor	Vane meter	8.50
Optical	Photodiode	Semiconductor	0.16
	Phototransistor	Semiconductor	0.65
	Photodetector	Semiconductor	0.03
	Infrared sensor	Semiconductor	7.50
	Solar cell	Photovoltaic	1.00
Position	Analog potentiometer	Resistive	1.50
	Digital potentiometer	Semiconductor	2.50
	LVDT	Transformer	7.50
	Rotary encoder	Optical	8.00
	Rotary encoder	Magnetic	5.00
Motion	Linear displacement	Resistive	2.50
	Rotary displacement	Resistive	3.50
	Displacement sensor	Capacitive	10.70
	Displacement sensor	Inductive	8.50
	Velocity sensor	Hall effect	2.50
	Velocity sensor	Electro-magnetic	3.50
	Velocity sensor	Rotational	2.50
	Optical - Photosensor	Semiconductor	0.16
	Optical - Infrared	Semiconductor	7.50

Presence, Proximity	Proximity sensor	Electro-magnetic	15.38
	Infrared	Semiconductor	7.50
Environmental	Altitude sensor	Piezoelectric	3.39
	Humidity sensor	Resistive	20.44
	Humidity sensor	Capacitive	20.44
	Accelerometer	Piezoresistive	15.00
	Accelerometer	Piezoelectric	13.00
	Strain Gauge	Semiconductor	23.00
	Smoke detection	Ionization	8.00
	Smoke detection	Photoelectric	6.50

5.1.9. Shafts

The shaft reliability model is shown by the following equation:

$$\lambda_{SH} = \lambda_{SH,B} * C_f * C_T * C_{DY} * C_{SC} \qquad (5\text{-}1\text{-}9\text{-}1)$$

where:

$\lambda_{SH,B}$ = Shaft base failure rate, failures/million cycles (See Equation 5-1-9-2)

C_f = Shaft surface finish multiplying factor (See Table 21)

C_T = Material temperature multiplying factor (See Equation 5-1-9-3 and 5-1-9-4)

C_{DY} = Shaft displacement multiplying factor (See Equation 5-1-9-5)

C_{SC} = Stress concentration factor for shaft discontinuities (See Equation 5-1-9-6)

$$\lambda_{SH,B} = \frac{1}{N} \qquad (5\text{-}1\text{-}9\text{-}2)$$

Where:

$\lambda_{SH,B}$ = Shaft base failure rate, failures/million cycles

N = Number of cycles to failure at application stress level, S_{ED}

S_{ED} = Material endurance limit, Ibs/in^2

The endurance limit, S_{ED} , for some common steels and alloys is shown in Table 20.

Table 20: Average Values of Endurance Limits

MATERIAL	ENDURANCE LIMIT S_{ED}
Steel, $\sigma_{T,ult} \leq 200\ kpsi$	0.50 $\sigma_{T,ult}$
Steel, $\sigma_{T,ult} > 200\ kpsi$	100 kpsi
Magnesium	0.35 $\sigma_{T,ult}$
Nonferrous Alloy	0.35 $\sigma_{T,ult}$
Aluminum Alloy (wrought)	0.40 $\sigma_{T,ult}$
Aluminum Alloy (cast)	0.30 $\sigma_{T,ult}$

Table 21: Shaft Surface Finish Factor

FINISH	C_f
Polished	1.0
Ground	0.89
Hot Rolled	$0.94 - 0.0046\, T_s + 8.37 \times 10^{-6} (T_s)^2$
Machined or Cold Drawn	$1.07 - 0.0051\, T_s + 2.21 \times 10^{-5} (T_s)^2 - 3.57 \times 10^{-8} (T_s)^3$
Forged	$0.75 - 4.06 \times 10^{-3}\, T_s + 7.58 \times 10^{-6} (T_s)^2$

Note: T_s = Tensile strength of material, kpsi

$$C_T = \frac{460+T_{AT}}{620} \text{ for } T_{AT} \geq 160\ °F \quad (5\text{-}1\text{-}9\text{-}3)$$

$$C_T = 1.0 \; for \; T_{AT} < 160\ °F \quad (5\text{-}1\text{-}9\text{-}4)$$

where: T_{AT} = Operating temperature, °F

$$C_{DY} = \frac{0.0043\, F}{Eb}\left[\frac{X^3}{I_X} + \frac{L^3}{I_L} + \frac{M^3}{I_M} + \frac{N^3}{I_N}\right] \quad (5\text{-}1\text{-}9\text{-}5)$$

E = Modulus of elasticity of shaft material, lbs/in2 (See Table 22)

F = Fluid radial unbalance force or load weight, lb

I = Shaft moment of inertia ($\pi d^4/64$), in^4

where: b = Specified shaft deflection, in (See Table 23)

X,L,M,N = Length of shaft section, in

Table 22: Shaft Material Strengths

Shaft Material	**Modulus of Elasticity E, mpsi**
Alloy steel	30
Stainless steel	29
High carbonsteel	30
Cast steel,carbon	30
Low alloy caststeel	30
Cast aluminum	10.3
Wroughtaluminum	10.3-10.6

Table 23: Allowable Shaft Bending

Applcation	**Allowable Shaft Detection b, inches ***
Actuator	0.007
Compressor	0.025
Motor	0.010
Pump	0.007

* Note 1: Default value = 0.007 inches

Note 2: If the application requires or permits a different allowable shaft bending, b can be adjusted accordingly.

$$C_{SC} = C_{SC,R} + C_{SC,G} \tag{5-1-9-6}$$

where: C_{SC} = Shaft stress concentration factor

$C_{SC,R}$ = Stress concentration factor due to tr ansition between shaft sections (See Equation 5-1-9-7)

$C_{SC,G}$ = Stress concentration factor due to shaft grooves (See Table 24)

A stress concentration factor for each shoulder radii can be found using the following equation:

$$C_{SC,R} = \left(\frac{0.3}{r/d}\right)^{0.2} * \left(\frac{D}{d}\right)^{1-r/d} \tag{5-1-9-7}$$

Where: r = Radius of fillet, in

D = Initial shaft diameter, in

d = Transitioned shaft diameter, in

Table 24 provides typical stress concentration factors for shaft grooves, $C_{SC,G}$. If there are no grooves in the shaft, $C_{SC,G}$ will be equal to 1.0.

Table 24: Stress Concentration Factor SSC,G for Shaft Groves

h/D	**h/r**						
	0.1	**0.5**	**1.0**	**2.0**	**4.0**	**6.0**	**8.0**
0.05	1.10	1.45	1.60	2.00	2.05	-	-
0.10	1.00	1.27	1.40	1.70	2.00	2.25	-
0.20	1.00	1.10	1.20	1.31	1.60	1.75	2.00
0.30	1.00	1.10	1.10	1.20	1.35	1.48	1.55

h = depth of shaft groove, r = radius of fillet or shaft groove

5.1.10. Battery

Mathematical model of the batteries as given below **[18]**:

$$\lambda = \lambda_0 * 10^{-9}/h \tag{5-1-10-1}$$

To obtain λ_0, use Table 25.

Table 25: λ_0 to calculate battery hazard rate

Device Type		λ_0
Batteries: primary cells*		20
Batteries: secondary cells	Ni-Cd	100
	Li-Ion	150

* Caution: life expectancy of these devices is limited.

5.1.11. Miscellaneous Parts

The system generally contains passive or non-moving parts such as pins, bolts, etc. The prediction of these non-moving parts reliabilities can be very hard. A typical published failure rates of some of these non-moving parts as given below.

- Axle: 0.01 failures/million hours
- Bolt: *0.12 failures per million hours*
- Bushing: *0.72 failures/million hours*
- Cam Mechanism: *6.1 failures per million hours*
- Fitting: *1.3 failures per million hours* for a threaded fitting and *2.4 failures per million hours* for a quick disconnect fitting
- Flywheel: *0.2 failures per million hours*

- Hinge: *0.5 failures per million cycles*
- Keys and Pins: *0.35 failures/million hours*
- Pillow Block: *5.0 failures per million revolutions*
- Rivet: *0.08 failures per million hours*
- Setscrew: *0.35 failures/million hours*
- Wire Rope: *17.5 failures per million operations*
- Power Screws: Failure rate of power screws calculated as given below.

$$\frac{\lambda_{PS}}{\lambda_{PS,B}} = \left(\frac{L_A}{L_S}\right)^3 \qquad (5\text{-}1\text{-}11\text{-}1)$$

where:

λ_{PS} = Failure rate of power screw, failures/million hours

$\lambda_{PS,B}$ = Base failure rate of power screw from published life, failures/millionhours

L_A = Equivalent radial load, lbs

L_S = Basic dynamic load rating, lbs

5.2. Electrical Equipment Reliability

In this section, calculation of electrical equipment's hazard rate is given. All hazard rate calculation is taken from **[19].** In this section, all part quality and environment factor values are depend on the Table 26 and Table 27 respectively, that is given below.

The quality of a part has a direct effect on the part failure rate and appears in the part models as a factor, π_Q. Such parts with their quality designators are shown in Table 26.

Table 26: Parts With Multi-Level Quality Specifications

Part	Quality Designators
Microcircuits	SI B, B-1 , Other: Quality Judged by Screening Level
Discrete semiconductors	JANTXV, JANTX, JAN
Capacitors, Established Reliability (ER)	D, C, S, R, B, P, M, L
Resistors, Established Reliability (ER)	S, R, P, M
Coils, Molded, R.F., Reliability	S, R, P, M
Relays, Established Reliability (ER)	R, P, M, L

All part reliability models include the effects of environmental stresses through the environmental factor, π_E. The descriptions of these environments are shown in Table 27.

Table 27: Use Environment Description

Environment	π_E Symbol	Description
Ground, Benign	G_B	Nonmobile, temperature and humidity controlled environments readily accessible to maintenance; includes laboratory instruments and test equipment, medical electronic equipment, business and scientific computer complexes, and missiles and support equipment in ground silos.
Ground, Fixed	G_F	Moderately controlled environments such as installation in permanent racks with adequate cooling air and possible installation in unheated buildings; includes permanent installatioonf air traff ¡c control radar and communications facilities.
Ground, Mobile	G_M	Equipment installed on wheeled or tracked vehicles and equipment manually transported; includes tactical missile ground support equipment, mobile communication equipment, tactical fire direction systems, handheld cammunications equipment, laser designations and range finders.

5.2.1. Diodes, Low Frequency

The general failure rate of diodes are given in equation (5-2-1-1).

$$\lambda_p = \lambda_b \pi_T \pi_S \pi_C \pi_Q \pi_E \ Failures/10^6 \ Hours \quad (5\text{-}2\text{-}1\text{-}1)$$

Table 28: Base Failure Rate λ_b

Diode Type/Application	λ_b
General Purpose Analog	.0038
Switching	.0010

Fast Recovery Power Rectifier	.025
Power Rectifier/Schottky Power Diode	.0030
Power Rectifier with High Voltage Stacks	.0050/Junction
Transient Suppressor/Varistor	.0013
Current Regulator	.0034
Voltage Regulator and Voltage Reference (Avalanche and Zener)	.0020

Table 29: Temperature Factor – π_T (Voltage Regulator, Voltage Reference and Current Regulator)

T_J(°C)	π_T	T_J(°C)	π_T
25	1.0	105	3.9
30	1.1	110	4.2
35	1.2	115	4.5
40	1.4	120	4.8
45	1.5	1 25	5.1
50	1.6	130	5.4
55	1.8	135	5.7
60	2.0	140	6.0
65	2.1	145	6.4
70	2.3	150	6.7
75	2.5	1 55	7.1
80	2.7	160	7.5
85	3.0	165	7.9
90	3.2	170	8.3
95	3.4	175	8.7
100	3.7		

$$\pi_T = exp\, exp\left(-1925\left(\frac{1}{T_J+273} - \frac{1}{298}\right)\right) \qquad (5\text{-}2\text{-}1\text{-}2)$$

T_J = Junction Temperature (°C)

Table 30: Temperature Factor – π_T (General Purpose Analog, Switching, Fast Recovery, Power Rectifier, Transient Suppressor)

T_J(°C)	π_T	T_J(°C)	π_T
25	1.0	105	9.0
30	1.2	110	10

35	1.4	115	11
40	1.6	120	12
45	1.9	125	14
50	2.2	130	15
55	2.6	135	16
60	3.0	140	18
65	3.4	145	20
70	3.9	150	21
75	4.4	155	23
80	5.0	160	25
85	5.7	165	28
90	6.4	170	30
95	7.2	175	32
100	8.0		

$$\pi_T = exp\ exp\left(-3091\left(\frac{1}{T_J+273}-\frac{1}{298}\right)\right) \quad (5\text{-}2\text{-}1\text{-}3)$$

T_J = Junction Temperature (°C)

Table 31: Electrical Stress Factor – π_S

Stress	π_S
Transient Suppressor, Voltage Regulator, Voltage Reference, Current Regulator	1.0
All Others:	
$V_S \leq .30$	0.054
$.3 < V_S \leq .40$	0.11
$.4 < V_S \leq .50$	0.19
$.5 < V_S \leq .60$	0.29
$.6 < V_S \leq .70$	0.42
$.7 < V_S \leq .80$	0.58
$.8 < V_S \leq .90$	0.77
$.9 < V_S \leq 1.00$	1 .0

For All Except Transient Suppressor, Voltage Regulator, Voltage Reference, or Current Regulator

$$\pi_S = .054 \quad (V_S \leq .3) \quad (5-2-1-4)$$

$$\pi_S = V_S^{2.43} \quad (.3 \leq V_S \leq 1) \quad (5-2-1-5)$$

$$V_S = Voltage\ Stress\ Ratio = \frac{Voltage\ Applied}{Voltage\ Rated} \quad (5\text{-}2\text{-}1\text{-}6)$$

Voltage is Diode Reverse Voltage

Table 32: Contact Consttuction Factor – π_C

Contact Construction	π_C
Metallurgically Bonded	1.0
Non-Metallurgically Bonded and Spring Loaded Contacts	2.0

Table 33: Quality Factor - π_Q

Quality	π_Q
JANTXV	0.7
JANTX	1.0
JAN	2.4
Lower	5.5
Plastic	8.0

Table 34: Environment Factor - π_E

Environment	π_E
G_B	1.0
G_F	6.0
G_M	9.0

○

5.2.2. Transistors, High Frequency, SI FET

The general failure rate of transistors are given in equation (5-2-2-1).

$$\lambda_p = \lambda_b \pi_T \pi_Q \pi_E\ Failures/10^6\ Hours \quad (5\text{-}2\text{-}2\text{-}1)$$

Table 35: Base Failure Rate λ_b

Transistor Type	λ_b
MOSFET	.060
JFET	.023

Table 36: Quality Factor - π_Q

Quality	π_Q
JANTXV	.50
JANTX	1.0
JAN	2.0
Lower	5.0

Table 37: Temperature Factor – π_T (Voltage Regulator, Voltage Reference and Current Regulator)

T_J(°C)	π_T	T_J(°C)	π_T
25	1.0	105	3.9
30	1.1	110	4.2
35	1.2	115	4.5
40	1.4	120	4.8
45	1.5	125	5.1
50	1.6	130	5.4
55	1.8	135	5.7
60	2.0	140	6.0
65	2.1	145	6.4
70	2.3	150	6.7
75	2.5	155	7.1
80	2.7	160	7.5
85	3.0	165	7.9
90	3.2	170	8.3
95	3.4	175	8.7
100	3.7		

$\pi_T = See\ Equation\ 5-2-1-2$

T_J = Junction Temperature (°C)

Table 38: Environment Factor - π_E

Environment	π_E
G_B	1.0
G_F	2.0
G_M	5.0

5.2.3. Resistors

The general failure rate of resistors are given in equation (5-2-3-1).

$$\lambda_p = \lambda_b \pi_T \pi_P \pi_S \pi_Q \pi_E\ Failures/10^6\ Hours \tag{5-2-3-1}$$

Table 39: Parameter Selection of Resistors

Resistor Style	Description	λ_b	Table 40 Column;	Table 42 Column;
RC	Resistor, Fixed, Composition (Insulated)	.0017	1	2
RCR	Resistor, Fixed, Composition (Insulated) Est. Rel.	.0017	1	2
RL	Resistor, Fixed, Film,Insulated	.0037	2	1
RLR	Resistor, Fixed, Film (Insulated), Est. Rel.	.0037	2	1
RN (R,C or N)	Resistor, Fixed, Film, Established Reliability	.0037	2	1
RM	Resistor, Fixed, Film, Chip, Established Reliability	.0037	2	1
RN	Resistor, Fixed Film (High Stability)	.0037	2	1
RD	Resistor, Fixed, Film (Power Type)	.0037	$\pi_T = 1$	1
RZ	Resistor Networks, Fixed, Film	.0019	1	$\pi_S = 1$
RB	Resistor, Fixed, Wirewound (Accurate)	.0024	2	1
RB R	Resistor, Fixed, Wirewound (Accurate) Est. Rel.	.0024	2	1
RW	Resistor, Fixed, Wirewound (Power Type)	.0024	2	2
RWR	Resistor, Fixed, Wirewound (Power Type) EstR. el.	.0024	2	2
RE	Resistor, Fixed, Wirewound (Power Type, Chassis Mounted)	.0024	2	2
RE R	Resistor, Fixed, Wirewound (Power Type, Chassis Mounted) Est. Rel.	.0024	2	2
RTH	Thermistor, (Thermally Sensitive Resistor), Insulated	.0019	$\pi_T = 1$	$\pi_S = 1$
RT	Resistor, Variable, Wirewound (Lead Screw Activated)	.0024	2	1
RTR	Resistor, Variable, Wirewound (Lead Screw Activated), Established Reliability	.0024	2	1

RR	Resistor, Variable, Wirewound, Precision	.0024	2	1
RA	Resistor, Variable, Wirewound (Low Operating Temperature)	.0024	1	1
RK	Resistor, Variable, Wirewound, Semi-Precision	.0024	1	1
RP	Resistor, Wirewound, Power Type	.0024	2	1
RJ	Resistor, Variable, Nonwirewound	.0037	2	1
RJ R	Resistor, Variable, Nonwirewound Est. Rel.	.0037	2	1
RV	Resistor,Variable,Composition	.0037	2	1
RQ	Resistor, Variable, Nonwirewound, Precision	.0037	1	1
RV C	Resistor, Variable, Nonwirewound	.0037	1	1

Table 40: Temperature Factor – π_T

T(°C)	Column 1	Column 2
20	.88	.95
30	1.1	1.1
40	1.5	1.2
50	1.8	1.3
60	2.3	1.4
70	2.8	1.5
80	3.4	1.6
90	4.0	1.7
100	4.8	1.9
110	5.6	2.0
120	6.6	2.1
130	7.6	2.3
140	8.7	2.4
150	10	2.5

$$\pi_T = exp\ exp\left(\frac{-Ea}{8.617\ x\ 10^{-5}}\left(\frac{1}{T+273} - \frac{1}{298}\right)\right) \tag{5-2-3-2}$$

Column 1: Ea = .2

Column 2: Ea = .08

T = Resistor Case Temperature. It can be approximated as ambient component temperature for low power dissipation non-power type resistors.

NOTE: π_T values shown should only be used up to the temperature rating of the device. For devices with ratings higher than 150°C, use the equation to determine π_T.

Table 41: Power Factor – π_P

Power Dissipation (Watts)	π_P
.001	.068
.01	.17
.13	.44
.25	.58
.50	.76
.75	.89
1.0	1.0
2.0	1.3
3.0	1.5
4.0	1.7
5.0	1.9
10	2.5
25	3.5
50	4.6
100	6.0
150	7.1

$\pi_P = (\text{Power Dissipation})^{.39}$ (5-2-3-3)

Table 42: Power Stress Factor – π_S

T(°C)	Column 1	Column 2
.1	.79	.66
.2	.88	.81
.3	.99	1.0
.4	1.1	1.2
.5	1.2	1.5
.6	1.4	1.8
.7	1.5	2.3
.8	1.7	2.8

.9	1.9	3.4

Column 1: π_S = .71e$^{1.1(S)}$ (5-2-3-4)

Column 2: π_S = .54e$^{2.04(S)}$ (5-2-3-5)

$$S = \frac{Actual\ Power\ Dissipation}{Rated\ Power} \quad (5\text{-}2\text{-}3\text{-}6)$$

Table 43: Environment Factor - π_E

Environment	π_E
G_B	1.0
G_F	4.0
G_M	16

Table 44: Quality Factor - π_Q

Quality	π_Q
Established Reliability Styles	
S	0.03
R	0.1
P	0.3
M	1.0
Non-Established Reliability Resistors (Most Two-Letter Styles)	3.0
Commercial or Unknown Screening Level	10

NOTE: Established reliability styles are failure rate graded (S, R, P, M) based on life testing defined in the applicable military device specification. This category usually applies only to three-letter styles with an "R" Suffix.

5.2.4. Capacitors

The general failure rate of capacitors are given in equation (5-2-4-1).

$$\lambda_p = \lambda_b \pi_T \pi_C \pi_V \pi_{SR} \pi_Q \pi_E \ Failures/10^6\ Hours \quad (5\text{-}2\text{-}4\text{-}1)$$

Table 45: General Capacitor Parameters

Capacitor Style	Description	λ_b	Table 46 Column;	Table 47 Column;	Table 48 Column;	π_{SR}
CP	Capacitor, Fixed, Paper-Dielectric, Direct Current (Hermetically Sealed in Metal Cases)	.00037	1	1	1	1
CA	Capacitor, By-pass, Radio - Interference Reduction, Paper Dielectric, AC and DC (Hermetically sealed in Metallic Cases)	.00037	1	1	1	1
CZ, CZR	Capacitor, Feed through, Radio Interference Reduction AC and	.00037	1	1	1	1

	DC (Hermetically sealed in metal cases), Established and Nonestablished Reliability					
CQ, CQR	Capacitor, Fixed Plastic (or Paper-Plastic) Dielectric (Hermetically sealed in metal, ceramic or glass cases), Established and Nonestablished Reliability	.00051	1	1	1	1
CH	Capacitor, Fixed, Metallized (Paper, Paper Plastic or Plastic Film) Dielectric, Direct Current (Hermetically Sealed in Metal Cases)	.00037	1	1	1	1
CHR	Capacitor, Fixed, Metallized Paper, Paper-Plastic Film or Plastic Film Dielectric	.00051	1	1	1	1
CFR	Capacitor, Fixed, Plastic (or Metallized Plastic) Dielectric, Direct Current in Non-Metal Cases	.00051	1	1	1	1
CRH	Capacitor, Fixed Supermetallized Plastic Film Dielectric (DC, AC or DC and AC) Hermetically Sealed in Metal Cases, Established Reliability	.00051	1	1	1	1
CM	Capacitors, Fixed, Mica Dielectric	.00076	2	1	2	1
CMR	Capacitor, Fixed, Mica Dielectric, Established Reliability	.00076	2	1	2	1
CB	Capacitor, Fixed, Mica Dielectric,Button Style	.00076	2	1	2	1
CY	Capacitor, Fixed, Glass Dielectric	.00076	2	1	2	1
CYR	Capacitor, Fixed, Glass Dielectric, Established Reliability	.00076	2	1	2	1
CK	Capacitor, Fixed, Ceramic Dielectric (General Purpose)	.00099	2	1	3	1
CKR	Capacitor, Fixed, Ceramic Dielectric (General Purpose), Established Reliability	.00099	2	1	3	1
CC, CCR	Capacitor, Fixed, Ceramic Dielectric (Temperature Compensating), Established and Nonestablished Reliabilihr	.00099	2	1	3	1

CDR	Capacitor, Chip, Muttiple Layer, Fixed, Ceramic Dielectric, Established Reliability	.0020	2	1	3	1
CSR	Capacitor, Fixed, Electrolytic (Solid Electrolyte), Tantalum, Established Reliability	.00040	1	2	4	See Table 49
CWR	Tantalum), Chip, Established Capacitor, Fixed, Electrolytic Reliability	.00005	1	2	4	See Table 49
CL	Capacitor, Fixed, Electrolytic (Nonsolid Electrolyte), Tantalum	.00040	1	2	4	1
CLR	Capacitor, Fixed, Electrolytic (Nonsolid Electrolyte), Tantalum, Established Reliability	.00040	1	2	4	1
CRL	Capacitor, Fixed, Electrolytic (Nonsolid Electrolyte), Tantalum Cathode	.00040	1	2	4	1
CU, CUR	Capacitor, Fixed, Electrolytic (Aluminum Oxide), Established Reliability and Nonestablished Reliability	.00012	2	2	1	1
CE	Capacitor, Fixed Electrolytic (DC, Aluminum, Dry Electrolyte, Polarized)	.00012	2	2	1	1
CV	Capacitor, Variable, Ceramic Dielectric (Trimmer)	.0079	1	1	5	1
PC	Capacitor, Variable (Piston Type, Tubular Trimmer	.0060	2	1	5	1
CT	Capacitor, Variable, Air Dielectric (Trimmer)	.0000072	2	1	5	1
CG	Capacitor, Fixed or Variable, Vacuum Dielectric	.0060	1	1	5	1

Table 46: Temperature Factor – π_T

T(°C)	Column 1	Column 2
20	.91	.79
30	1.1	1.3
40	1.3	1.9
50	1.6	2.9
60	1.8	4.2
70	2.2	6.0

80	2.5	8.4
90	2.8	11
100	3.2	15
110	3.7	21
120	4.1	27
130	4.6	35
140	5.1	44
150	5.6	56

$\pi_T = See\ Equation\ 5-2-3-2$
Column 1: Ea = .15

Column 2: Ea = .35
T = Capacitor Ambient Temperature
NOTE:
1. π_T values shown should only be use up to the temperature rating of the device.
2.For devices with ratings higher than 150°C, use the equation to determine π_T (for applications above 150°C).

Table 47: Capacitance Factor – π_C

Capacitance, C(μF)	Column 1	Column 2
.000001	.29	.04
.00001	.35	.07
.0001	.44	.12
.001	.54	.20
.01	.66	.35
.05	.76	.50
.1	.81	.59
.5	.94	.85
1	1.0	1.0
3	1.1	1.3
8	1.2	1.6
18	1.3	1.9
40	1.4	2.3
200	1.6	3.4
1000	1.9	4.9
3000	2.1	6.3

10000	2.3	8.3
30000	2.5	11
60000	2.7	13
120000	2.9	15

Column 1: $\pi_C = C^{.09}$ (5-2-4-2)
Column 2: $\pi_C = C^{.23}$ (5-2-4-3)

Table 48: Voltage Stress Factor – π_V

Voltage Stress	Column 1	Column 2	Column 3	Column 4	Column 5
0.1	1.0	1.0	1.0	1.0	1.0
0.2	1.0	1.0	1.0	1.0	1.1
0.3	1.0	1.0	1.1	1.0	1.2
0.4	1.1	1.0	1.3	1.0	1.5
0.5	1.4	1.2	1.6	1.0	2.0
0.6	2.0	2.0	2.0	2.0	2.7
0.7	3.2	5.7	2.6	15	3.7
0.8	5.2	19	3.4	130	5.1
0.9	8.6	59	4.4	990	6.8
1	14	166	5.6	5900	9.0

$$Column\ 1:\ \pi_V = \left(\frac{S}{.6}\right)^5 + 1 \quad (5\text{-}2\text{-}4\text{-}4)$$

$$Column\ 2:\ \pi_V = \left(\frac{S}{.6}\right)^{10} + 1 \quad (5\text{-}2\text{-}4\text{-}5)$$

$$Column\ 3:\ \pi_V = \left(\frac{S}{.6}\right)^3 + 1 \quad (5\text{-}2\text{-}4\text{-}6)$$

$$Column\ 4:\ \pi_V = \left(\frac{S}{.6}\right)^{17} + 1 \quad (5\text{-}2\text{-}4\text{-}7)$$

$$Column\ 5:\ \pi_V = \left(\frac{S}{.6}\right)^3 + 1 \quad (5\text{-}2\text{-}4\text{-}8)$$

$$S = \frac{Operating\ Voltage}{Rated\ Voltage} \quad (5\text{-}2\text{-}4\text{-}9)$$

Note: Operating voltage is the sum of applied DC voltage and peak AC voltage.

Table 49: Series Resistance Factor (Tantalum CSR Style Capacitors Only) – π_{SR}

Circuit Resistance, CR (ohms/volt)	π_{SR}
>0.8	.66
>0.6 to 0.8	1.0
>0.4 to 0.6	1.3
>0.2 to 0.4	2.0
>0.1 to 0.2	2.7
0 to 0.1	3.3

$$CR = \frac{Eff.Res.Between\ Cap.and\ Pwr.Supply}{Voltage\ Applied\ to\ Capacitor} \quad (5\text{-}2\text{-}4\text{-}10)$$

Table 50: Quality Factor - π_Q

Quality	π_Q
Established Reliability Styles	
D	.001
C	.01
S,B	.03
R	.1
P	.3
M	1.0
L	1.5
Non-Established Reliability Capacitors (Most Two-Letter Styles)	3.0
Commercial or Unknown Screening Level	10

NOTE: Established reliability styles are failure rate graded (D, C, S, etc.) based on life testing defined in the applicable military device specification. This category usually applies only to three-letter styles with an "R" Suffix.

Table 51: Environment Factor - π_E

Environment	π_E
G_B	1.0
G_F	10
G_M	20

5.2.5. Inductive Devices, Coils

The general failure rate of coils are given in equation (5-2-5-1).

$$\lambda_p = \lambda_b \pi_T \pi_Q \pi_E \ Failures/10^6\ Hours \quad (5\text{-}2\text{-}5\text{-}1)$$

Table 52: Base Failure Rate λ_b

Transistor Type	λ_b
Fixed Inductor or Choke	.000030
Variable Inductor	.000050

Table 53: Quality Factor - π_Q

Quality	π_Q
S	.03
R	.10
P	.30
M	1.0
MIL-SPEC	1.0
Lower	3.0

Table 54: Temperature Factor – π_T

T_{HS} (°C)	π_T
20	.93
30	1.1
40	1.2
50	1.4
60	1.6
70	1.8
80	1.9
90	2.2
100	2.4
110	2.6
120	2.8
130	3.1
140	3.3
150	3.5
160	3.8
170	4.1
180	4.3
190	4.6

$$\pi_T = exp\ exp\left(\frac{-.11}{8.617\ x\ 10^{-5}}\left(\frac{1}{T_{HS}+273} - \frac{1}{298}\right)\right) \qquad (5\text{-}2\text{-}5\text{-}2)$$

T_{HS} = Hot Spot Temperature (°C)

Table 55: Environment Factor - π_E

Environment	π_E
G_B	1.0
G_F	6.0
G_M	12

5.2.6. Rotating Devices, Motors

The model is dictated by two failure modes, bearing failures and winding failures.

$$\lambda_P = \left[\frac{\lambda_1}{A\alpha_B} + \frac{\lambda_2}{B\alpha_W}\right] x\ 10^6\ Failures\ /\ 10^6\ Hours \qquad (5\text{-}2\text{-}6\text{-}1)$$

Table 56: Bearing & Winding Characteristic Life – α_B and α_W

T_A(°C)	α_B (Hr.)	α_W (Hr.)	T_A(°C)	α_B (Hr.)	α_W (Hr.)

0	3600	6.4e+06	70	22000	1.1e+05
10	13000	3.2e+06	80	14000	7.0e+04
20	39000	1.6e+06	90	9100	4.6e+04
30	78000	8.9e+05	100	6100	3.1e+04
40	80000	5.0e+05	110	4200	2.1e+04
50	55000	2.9e+05	120	2900	1.5e+04
60	35000	1.8e+05	130	2100	1.0e+04
			140	1500	7.5e+03

$$\alpha_B = \left[10^{\left(2.534-\frac{2357}{T_A+273}\right)} + \frac{1}{10^{\left(20-\frac{4500}{T_A+273}\right)}+300}\right]^{-1} \qquad (5\text{-}2\text{-}6\text{-}2)$$

$$\alpha_W = 10^{\left[\frac{2357}{T_A+273}-1.83\right]} \qquad (5\text{-}2\text{-}6\text{-}3)$$

α_W = Weibull Charactistic Life for the Motor Bearing

α_B = Weibull Characteristic Life for the Motor Windings

T_A = Ambient Temperature (°C)

NOTE: See Equation (5-2-6-4) and Figure 9 for method to calculate α_B and α_W when temperature is not constant.

The following equation can be used to calculate a weighted characateristic life for both bearings and windings.

$$\alpha = \frac{(h_1+h_2+h_3+\cdots+h_m)}{\frac{h_1}{\alpha_1}+\frac{h_2}{\alpha_2}+\frac{h_3}{\alpha_3}+\cdots+\frac{h_m}{\alpha_m}} \qquad (5\text{-}2\text{-}6\text{-}4)$$

where:

α: either α_B or α_W

α_1: Bearing (or Winding Life at T_1); α_2: Bearing (or Winding Life at T_2)

h_1: Time at temperature T_1

h_2: Time to cycle from temperature T_1 to T_3

h_3: Time at temperature T_3

h_m: Time at temperature T_m

Note: $T_2 = \frac{T_1+T_3}{2}$ and $T_4 = \frac{T_3+T_1}{2}$

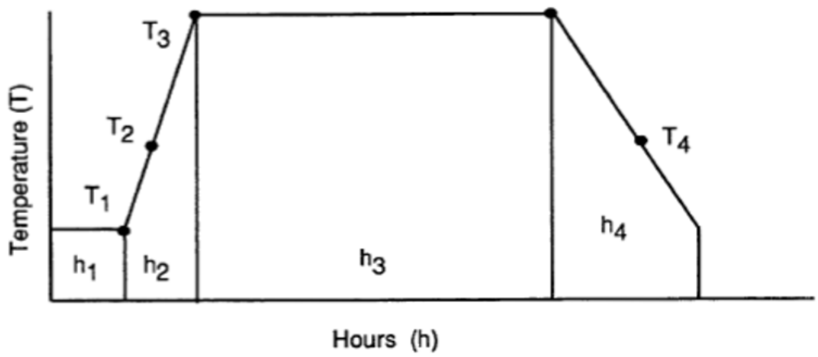

Figure 9: Thermal Cycle

Table 57: A and B Determination

Motor Tvpe	A	B

Electrical (General)	1.9	1.1
Sensor	.48	.29
Servo	2.4	1.7
Stepper	11	5.4

Table 58: λ_1 and λ_2 Determination

$\frac{LC}{\alpha_B}$ or $\frac{LC}{\alpha_W}$	λ_1 or λ_2
0 - .10	.13
.11 - -20	.15
.21 - .30	.23
.31 - .40	.31
.41 - .50	.41
.51 - .60	.51
.61 - .70	.61
.71 - .80	.68
.81 - .90	.76
>1.0	1.0

LC is the system design life cycle (in hours), or the motor preventive maintenance interval, if motors will be periodically replaced or .refurbished. Determine λ_1 and λ_2 separately based on the respective $\frac{LC}{\alpha_B}$ *and* $\frac{LC}{\alpha_W}$ ratios.

5.2.7. Relays, Mechanical

The general failure rate of relays are given in equation (5-2-7-1).

$$\lambda_p = \lambda_b \pi_L \pi_C \pi_{CYC} \pi_F \pi_Q \pi_E \; Failures/10^6 \; Hours \quad (5\text{-}2\text{-}7\text{-}1)$$

Table 59: Base Failure Rate λ_b

	Rated Temperature	
T_A(°C)	85°C[1]	125°C[2]
25	.0059	.0059
30	.0067	.0066
35	.0075	.0073
40	.0084	.0081
45	.0094	.0089
50	.010	.0098
55	.012	.011
60	.013	.012
65	.014	.013
70	.016	.014
75	.017	.015
80	.019	.017
85	.021	.018

90	.019
95	.021
100	.022
105	.024
110	.026
115	.027
120	.029
125	.031

1. $\lambda_b = .0059 \, exp \, exp \left(\frac{-.19}{8.617 \, x \, 10^{-5}} \left(\frac{1}{T+273} - \frac{1}{298} \right) \right)$ (5-2-7-2)

2. $\lambda_b = .0059 \, exp \, exp \left(\frac{-.17}{8.617 \, x \, 10^{-5}} \left(\frac{1}{T+273} - \frac{1}{298} \right) \right)$ (5-2-7-3)

T_A = Ambient Temperature (°C)

Table 60: Load Stress Factor – π_L

S	Load Type		
	Resistive[1]	**Inductive**[2]	**Lamp**[3]
.05	1.00	1.02	1.06
.10	1.02	1.06	1.28
.20	1.06	1.28	2.72
.30	1.15	1.76	9.49
.40	1.28	2.72	54.6
.50	1.48	4.77	
.60	1.76	9.49	
.70	2.15	21.4	
.80	2.72		
.90	3.55		
1.00	4.77		

1 : $\pi_L = \left(\frac{S}{.8}\right)^2 + 1$ (5-2-7-4)

2 : $\pi_L = \left(\frac{S}{.4}\right)^2 + 1$ (5-2-7-5)

3 : $\pi_L = \left(\frac{S}{.2}\right)^2 + 1$ (5-2-7-6)

$S = \frac{Operating\ Load\ Current}{Rated\ Resistive\ Load\ Current}$ (5-2-7-7)

For single devices which switch two different load types, evaluate π_L for each possible stress load type combination and use the worse case (largest π_L).

Table 61: Contact Form Factor – π_C (Applies to Active Conducting Contacts)

Contact Form	π_C

SPST	1.00
DPST	1.50
SPDT	1.75
3PST	2.00
4PST	2.50
DPDT	3.00
3PDT	4.25
4PDT	5.50
6PDT	8.00

Table 62: Cycling Factor – π_{CYC} (Applies to Active Conducting Contacts)

Cycle Rate (Cycles per Hour)	**π_{CYC} (MIL - SPEC)**
≥ 1.0	$\left(\frac{Cycles\ per\ Hour}{10}\right)$
< 1.0	0.1
Cycle Rate (Cycles per Hour)	**π_{CYC} (Commercial Quality)**
> 1000	$\left(\frac{Cycles\ per\ Hour}{100}\right)^2$
10 - 1000	$\left(\frac{Cycles\ per\ Hour}{10}\right)$
<10	1.0

NOTE: Values of π_{CYC} for cycling rates beyond the basic design limitations of the relay are not valid. Design specifications should be consulted prior to evaluation of π_{CYC}.

Table 63: Quality Factor - π_Q

Quality	**π_Q**
R	.10
P	.30
X	.45
U	.60
M	1.0
L	1.5
MIL-SPEC, Non-Est. Rel.	1.5
Commercial	2.9

Table 64: Environment Factor - π_E

Environment	**π_E**
G_B	1.0
G_F	2.0
G_M	15

Table 65: Environment Factor - π_E

Contact Rating	Application Type	Construction Type	π_F
Signal Current (Low mv and ma)	Dry Circuit	Armature (Long)	4
		Dry Reed	6
		Mercury Wetted	1
		Magnetic Latching	4
		Balanced Armature	7
		Solenoid	7
0-5 Amp	General Purpose	Armature (Long)	3
		Balanced Armature	5
		Solenoid	6
	Sensitive (0 - 100 mw)	Armature (Long and Short)	5
		Mercury Wetted	2
		Magnetic Latching	6
		Meter Movement	100
		Balanced Armature	10
	Polarized	Armature (Short)	10
		Meter Movement	100
	Vibrating Reed	Dry Reed	6
		Mercury Wetted	1
	High Speed	Armature (Balanced and Short)	25
		Dry Reed	6
	Thermal Time Delay	Bimetal	10
	Electronic Time Delay, Non-Thermal		9
	Latching, Magnetic	Dry Reed	10
		Mercury Wetted	5
		Balanced armature	5
5-20 Amp	High Voltage	Vacuum (Glass)	20
		Vacuum (Ceramic)	5
	Medium Power	Armature (Long and Short)	3
		Mercury Wetted	1
		Magnetic Latching	2
		Mechanical Latching	3
		Balanced Armature	2
		Solenoid	2
25-600 Amp	Contactors (High Current)	Armature (Short)	7
		Mechanical Latching	12

Balanced Armature	10
Solenoid	5

5.2.8. Connectors, General

The general failure rate of connectors are given in equation (5-2-8-1).

$$\lambda_p = \lambda_b \pi_T \pi_K \pi_Q \pi_E \ Failures/10^6 \ Hours \quad (5\text{-}2\text{-}8\text{-}1)$$

Table 66: Base Failure Rate λ_b

Description	λ_b
Circular/Cylindrical	.0010
Card Edge (PCB)*	.040
Hexagonal	.15
Rack and Panel	.021
Rectangular	.046
RF Coaxial	.00041
Telephone	.0075
Power	.0070
Triaxial	.0036

Table 67: Temperature Factor – π_T

T_o(°C)	π_T
20	.9 1
30	1.1
40	1.3
50	1.5
60	1.8
70	2.0
80	2.3
90	2.7
100	3.0
110	3.4
120	3.7
130	4.1
140	4.6
150	5.0
160	5.5
170	6.0
180	6.5
190	7.0
200	7.5
210	8.1

220	8.6
230	9.2
240	9.8
250	10.

$$\pi_T = exp\ exp\left(\frac{-.14}{8.617\ x\ 10^{-5}}\left(\frac{1}{T_0+273} - \frac{1}{298}\right)\right) \qquad (5\text{-}2\text{-}8\text{-}2)$$

T_0 = Connector Ambient + ΔT

ΔT = Connector Insert Temperature Rise (See Table 68)

Table 68: Default Insert Temperature Rise (ΔT (°C)) Determination

Amperes			**Contact Gauge**		
Per Contact	30	22	20	16	12
2	10	4	2	1	0
3	22	8	5	2	1
4	37	13	8	4	1
5	56	19	13	5	2
6	79	27	18	8	3
7		36	23	10	4
8		46	30	13	5
9		57	37	16	6
10		70	45	19	7
15			96	41	15
20				70	26
25				106	39
30					54
35					72
40					92

$\Delta T = 3.256\ (i)^{1.85}$	32 Gauge Contacts
$\Delta T = 2.856\ (i)^{1.85}$	30 Gauge Contacts
$\Delta T = 2.286\ (i)^{1.85}$	28 Gauge Contacts
$\Delta T = 1.345\ (i)^{1.85}$	24 Gauge Contacts
$\Delta T = 0.989\ (i)^{1.85}$	22 Gauge Contacts
$\Delta T = 0.640\ (i)^{1.85}$	20 Gauge Contacts
$\Delta T = 0.429\ (i)^{1.85}$	18 Gauge Contacts
$\Delta T = 0.274\ (i)^{1.85}$	16 Gauge Contacts
$\Delta T = 0.100\ (i)^{1.85}$	12 Gauge Contacts

ΔT = Insert Temperature Rise

I = Amperes per Contact

RF Coaxial Connectors	ΔT = 5°C
RF Coaxial Connectors (High Power Applications)	ΔT = 50°C

Table 69: Mating/ Unmating Factor – π_K

Mating/ Unmating Cycles (per 1000 hours)	π_K
0 to .05	1.0
> .05 to .5	1.5
> .5 to 5	2.0
> 5 to 50	3.0
> 50	4.0

*One cycle includes both connect and disconnect.

Table 70: Quality Factor - π_Q

Quality	π_Q
MIL-SPEC	1
Lower	2

Table 71: Environment Factor - π_E

Environment	π_E
G_B	1.0
G_F	1.0
G_M	8.0

5.2.9. Connectors, Sockets

The general failure rate of connectors are given in equation (5-2-9-1).

$$\lambda_p = \lambda_b \pi_P \pi_Q \pi_E \ Failures/10^6 \ Hours \quad (5\text{-}2\text{-}9\text{-}1)$$

Table 72: Base Failure Rate λ_b

Description	λ_b
Dual-ln-Line Package	.00064
Single-ln-Line Package	.00064
Chip Carrier	.00064
Pin Grid Array	.00064
Relay	.037
Transistor	.0051
Electron Tube, CRT	.011

Table 73: Quality Factor - π_Q

Quality	π_Q
MIL-SPEC	.3
Lower	1.0

Table 74: Active Pins Factor – π_P

Number of Active Contacts	π_P	Number of Active Contacts	π_P
1	1.0	55	6.9
2	1.5	60	7.4
3	1.7	65	7.9
4	1.9	70	8.4
5	2.0	75	8.9
6	2.1	80	9.4
7	2.3	85	9.9
8	2.4	90	10
9	2.5	95	11
10	2.6	100	12
11	2.7	1 05	12
12	2.8	110	13
13	2.9	115	13
14	3.0	120	14
15	3.1	1 25	14
16	3.2	130	15
17	3.3	135	16
18	3.4	140	16
19	3.5	145	17
20	3.6	150	18
25	4.1	1 55	18
30	4.5	160	19
35	5.0	165	20
40	5.5	170	20
45	5.9	175	21
50	6.4	180	22

$$\pi_P = exp\left(\frac{N-1}{10}\right)^q \qquad (5\text{-}2\text{-}9\text{-}2)$$

$q = .39$

N = Number of Active Pins

Table 75: Environment Factor - π_E

Environment	π_E
G_B	1.0
G_F	3.0
G_M	14

5.2.10. Quartz Cyrstals

The general failure rate of crystals are given in equation (5-2-10-1).

$$\lambda_p = \lambda_b \pi_Q \pi_E \ Failures/10^6 \ Hours \quad (5\text{-}2\text{-}10\text{-}1)$$

Table 76: Base Failure Rate λ_b

Frequency, f(MHz)	λ_b
0.5	.011
1.0	.013
5.0	.019
10	.022
15	.024
20	.026
25	.027
30	.028
35	.029
40	.030
45	.031
50	.032
55	.033
60	.033
65	.034
70	.035
75	.035
80	.036
85	.036
90	.037
95	.037
100	.037
105	.038

$$\lambda_b = .013(f)^{.23} \quad (5\text{-}2\text{-}10\text{-}2)$$

Table 77: Environment Factor - π_E

Environment	π_E
G_B	1.0
G_F	3.0
G_M	10

Table 78: Quality Factor - π_Q

Quality	π_Q
MIL-SPEC	1.0
Lower	2.1

5.2.11. Fuses

The general failure rate of fuses are given in equation (5-2-11-1).

$$\lambda_p = \lambda_b \pi_E \; Failures/10^6 \; Hours \qquad (5\text{-}2\text{-}11\text{-}1)$$

Table 79: Base Failure Rate λ_b

Type	λ_b
W-F-1726, W-F-1814, MIL-F-5372, MIL-F-23419, ML-F-15160	.010

Table 80: Environment Factor - π_E

Environment	π_E
G_B	1.0
G_F	2.0
G_M	8

6. PROBABILITY OF TASK COMPLETION (POTC)

Long-term autonomous operations of the robot is very important for the industrial applications. Reliability is very important concept to sustain autonomy in these industrial areas. Mobile robots reliability depends on the subsytem, components and parts failure rate, usage time of these components, and environmental conditions. In order to increase the lifetime of mobile robots, prognostics-aware systems can be used. At these systems, robot should have known reliability and task completion probability. The probability of task completion (PoTC) is a metric that shows how successful mobile robots have completed a given task. PoTC could be used for lifetime extension of the system, sustaining autonomy, task allocation for multi-robot systems etc. by using reliability of robot and distance travelled along task. The lifetime of the robot maybe increased if the robot is capable of knowing health status and making route selection decision accordingly. Thus, using the reliability during decision making results sustainable autonomous operations for the robot. Probability of task completion (PoTC) for the robot is calculated by Equation (6-1).

$$PoTC = R^d \tag{6-1}$$

Where R and d are reliability of robot and total distance travelled by robot for given task respectively.

7. USE CASE SCENARIO IMPLEMENTATION

In order to successful reliability prediction, calculate component level of system failure, developing reliability estimation model and performing tests on components, subsystems and systems.

In the use case scenario, we select exponential model (in Section 4.1.1 and Equation 4-1-1-3) and we assumed that only series and parallel systems are used and some stresses, parameters, components are negligible. The failure rate prediction process consists of the following steps:

i. Divide system into sub-systems and components.
ii. Select the reference failure rate for each component from the Section 5.
iii. Determine operational conditions and stresses.
iv. Select appropraite accelerated life test if necessary from Section 4.
v. Sum up the component failure rates and calculate sub-systems and system failure rates by using series and parallel block diagrams in Section 3.
vi. Use appropriate life distribution model (In our case Exponential Distribution is selected).
vii. Calculate system reliability.
viii. Calculate system PoTC of the robot from the Section 6.

In the scenario, we use Autonomous Transport Vehicle (ATV) that can interact with Human Machine Interface (HMI) and robot arms and is used in load carrying tasks in the Smart Factory. The ATV shown in Figure 10 is 1392 mm long, 810 mm wide and 1013 mm high. The ATV is equipped with ZED stereo camera, SICK S300 Expert laser scanner, bumper stop system and some auxiliary sensors. In addition, there is an industrial PC and Jetson TX2 for operating emergency stop system, motion system with 4 caster and 2 driving wheels, positioning system and high level controller capabilities.

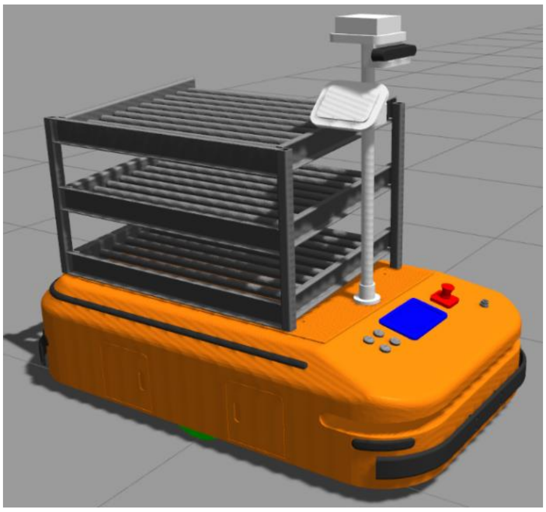

Figure 10: Autonomous Transfer Vehicle

In the scenario we are interested in only three modules (mobility, power and sensing) of our robot. In each module includes different sub-modules that can be series or parallel with each other. There are two mobility modules in the system each of them includes motor and encoder sub-modules and they are parallel with each other. In the sensing module, there is only one sub-module which is SICK-S300 laser sensor module. In the power module, there are two sub-modules, one of them is battery and the other one is power card. Power card sub-module includes buck converter, capacitor, inductor, diode and fuse. In this module, power card and battery sub-modules linked series with each other. In the power card sub-module, buck converter, capacitor, inductor, diode and fuse linked with series. The components making up each module are listed in Table 81.

Table 81: Use Case Scenario Module, Sub-Module and Components List

Module	MOBILITY		SENSING	POWER					
Sub Module	Motor	Encoder	Laser Sensor	Power Card					Battery
Components	-	-	-	Capacitor	Inductor	Buck Converter	Diode	Fuse	-

System block diagram is shown in the Figure 11. As can be seen at the figure, each mobility system connected with the other as series, which means one of the mobility system fails, all mobility modules give fault. Mobility and sensing modules are parallel. At the whole system, power module linked series with parallel connection between mobility and sensing modules.

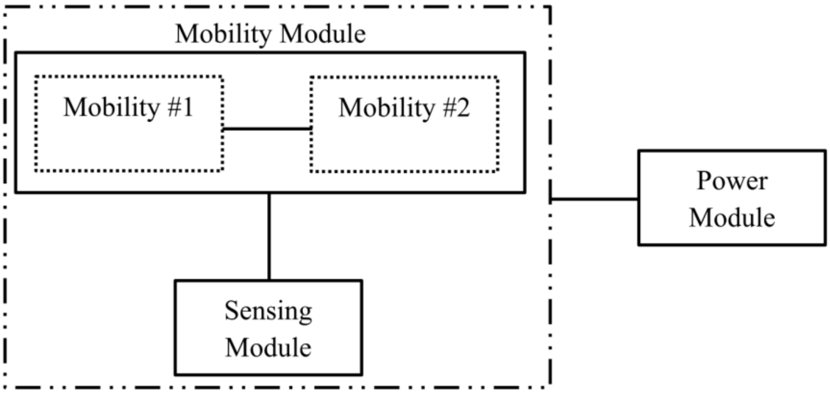

Figure 11: Use Case General Block Diagram

In the motor sub-module, failure rate of this component is selected as *15.09 failures/million hours* by using **[20]**. In encoder sub-module, we selected magnetic rotary encoder unit. Only use parameters λ_S (other parameters are negligible) in Equation (5-1-8-1) and Table 19, the failure rate of encoder unit selected as *5.00 failures/million hours*.

In the sensor module, there is only one component which is SICK S300 Laser Sensor and the failure rate of this component selected as *0.08 failures/million hours* using product datasheet **[21]**.

In order to calculate hazard rate of the power card sub-module, we utilized Section (5.2.1) for diodes, Section (5.2.4) for capacitors and Section (5.2.5) for inductors. In addition, hazard rate of the fuse in the power card sub-modules selected as *0.01 failures/million hours* by using Section (5.2.11). Hazard rate of the selected buck converter (LM 2596), is found as *0.00265 failures/million hours* **[22]**. There is one more component in the Power Module which is battery and the failure rate of this component selected as *0.1 failures/million hours* by using Section (5.1.10).

General failure rates and reliabilities of the all components at 35 °C are shown in Table 82.

Table 82: General Failure Rates and Reliabilities of Components

Component	**Failure Rate**	**Reliability**
DC Motor	15.09 failures/10^{-6} hours	0.985023283518
Encoder	5.0 failures/10^{-6} hours	0.995012479193
Laser Sensor	0.08 failures/10^{-6} hours	0.9999200032
Capacitor	0.013799 failures/10^{-6} hours	0.999986201043
Inductor	0.00074154 failures/10^{-6} hours	0.999999258464

Buck Converter	0.0027 failures/10^{-6} hours	0.999997350004
Diode	0.002619486 failures/10^{-6} hours	0.999997380518
Fuse	0.01 failures/10^{-6} hours	0.99999000005
Battery	0.1 failures/10^{-6} hours	0.999900005

Using Table 82 and Section 3, hazard rate of the system λ_{sys} calculated as *0.80409211851 failures/million hours*. In order to calculate the reliability of the system, we use Exponential Distribution function with the system hazard rate and time. Usage time selected as 1000 hours. The reliability of the system R_{sys} calculated as *0.982120841987*.

This test is repeated at different temperature conditions (25 ℃-175 ℃, with 5℃ temperature step). Power module system hazard rate and reliability results at some different temperature cases are given in Table 83.

Table 83: System Hazard Rate and Reliability at Different Temperature Conditions

Temperature ℃	**Failure Rate**	**Reliability**
25 ℃	0.12658411 failures/10^{-6} hours	0.982124010279
35 ℃	0.80409212 failures/10^{-6} hours	0.982120841987
50 ℃	0.13565832 failures/10^{-6} hours	0.982115098324
75 ℃	0.14855047 failures/10^{-6} hours	0.982102436828
100 ℃	0.16614629 failures/10^{-6} hours	0.982085156091
125 ℃	0.18936132 failures/10^{-6} hours	0.982062357204
150 ℃	0.21910539 failures/10^{-6} hours	0.982033147108
175 ℃	0.25624802 failures/10^{-6} hours	0.981996672499

The change in reliability of the system at different temperatures is given the Figure 12.

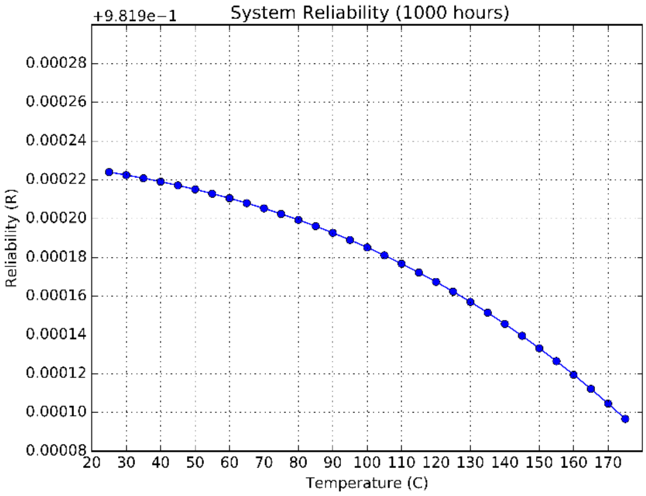

Figure 12: Reliability of System at Different Temperatures (25 ℃-175 ℃)

When we examine the the figure, we see that, when the temperature increases, reliability of the system decrease because of the characteristic of the electrical components.

Using calculated reliability at 35 ℃, we also obtained the PoTC of the system. In this scenario, robot is located at simulation environment that is created by GAZEBO and shown in Figure 13.

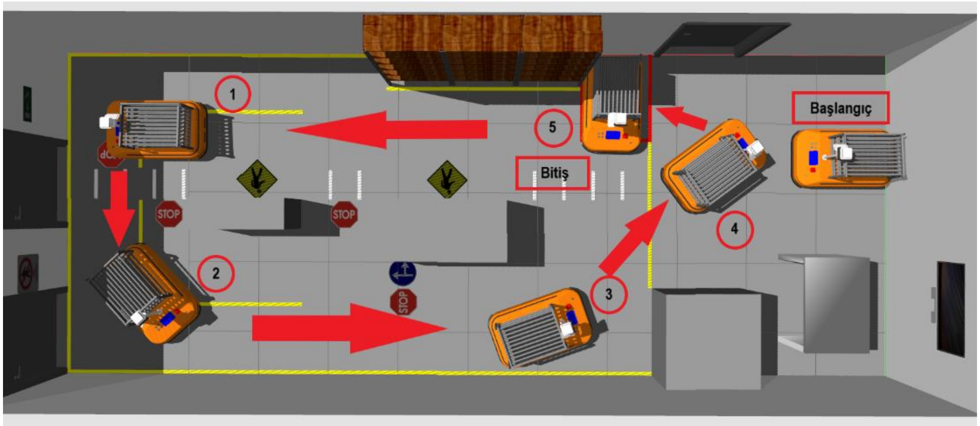

Figure 13: GAZEBO Test Environment

The ATV follows the path which starts from beginning point to Location 1, Location 2, ..., Location 5 that is also shown in figure given above. Each x and y position of these locations are given in Table 84.

Table 84: Locations of Some Specific Points

Point	X Coordinate (m)	Y Coordinate (m)
Beginning Point	0.7	1.50
Point 1	10.4	1.13
Point 2	10.5	3.45
Point 3	4.97	3.91
Point 4	1.53	1.62
Point 5	3.98	0.73

Followed path and each distance between neighbour points are shown in Figure 14.

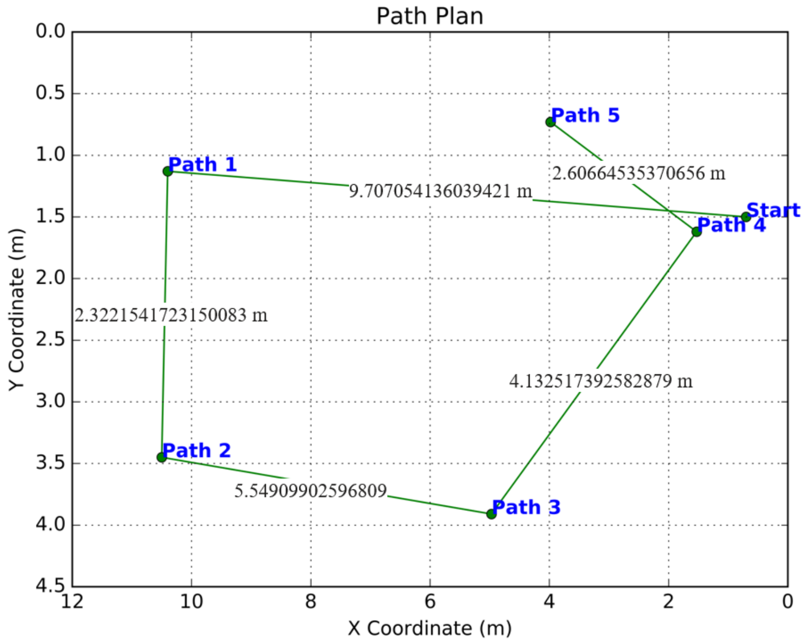

Figure 14: Followed Paths and Distance Between Each Neighbour Points

PoTC of the system is calculated for five different distance and result is shwon in Figure 15.

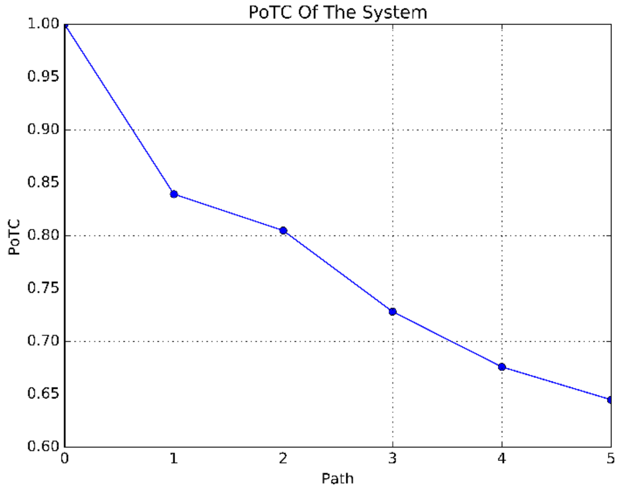

Figure 15: System PoTC for Each Route Segment

As shown in the Figure 15, system PoTC is decreased, when travelled distance increases. Pseudocode of all system is shown in Table 85.

Table 85: Pseudocode of All System

1.	*Calculate Hazard Rate of All Components*

	Calculate Hazard Rate of Motor
	Calculate Hazard Rate of Encoder
	Calculate Hazard Rate of Sensor
	Calculate Hazard Rate of Battery
	Calculate Hazard Rate of Power Module
	    Calculate Hazard Rate of Diode
	    Calculate Hazard Rate of Capacitor
	    Calculate Hazard Rate of Inductor
	    Calculate Hazard Rate of Buck Converter
	    Calculate Hazard Rate of Fuse
	Return Hazard Rates of Each Component

2.	*Calculate Each Component Reliability*
	λ,and usage time t *$R(t) = exp(-\lambda t)$* *Return Reliability of Each Component*
3.	*Configure The System*
	$Mobility_1$=parallel (motor1, encoder1) and $Mobility_2$=parallel (motor2, encoder2) *MobilityModule=series($Mobility_1$, $Mobility_2$)* *PowerCard=series(inductor,capacitor,diode,fuse,buck converter)* *PowerModule=series(PowerCard,Battery)* *R_{system}=series(parallel(SensingModule, MobilityModule),PowerModule)* *Return R_{system}*

4. Calculate PoTC of the System

R_{system} *and travelled distance, d*

$PoTC = R_{system}{}^{d}$

Return PoTC

8. PHM TOOL SOFTWARE ARCHITECTURAL DESIGN

8.1. Introduction

The user can create his own system by adding modules and components with phm tools. Phm tools calculate the reliability and failure values of the system, visualize the calculations and show the real-time analysis to the user. The user can use the built in functions which available in phm tools to calculate reliability and failure rate values, or customize his calculations with his own formulas and variables.

8.2. Software Design

8.2.1. Configuration Tab

The user can create his own robot model as he wishes. For example, in the “Adding Module and Component” section, the user first specifies the module name, task time, and serial or parallel status of the module type. Then, components are added to the created module. Module must be created in advance to add components. When creating the component, the module to be added is selected first. The component name, failure rate value, quantity and type are then determined.

In the “Edit Module and Component” section, the user can edit the type of modules and components that have been previously added. By selecting the "Relationship of component" option, the user can create the system in serial or parallel. For this, the module must have more than one component. If desired, the user can update the previous relationship. If "Relationship of component" is not selected, the type of the existing component is changed.

The interface and flow diagram design studies of the Configuration Tab are given in Figure 16 - 17.

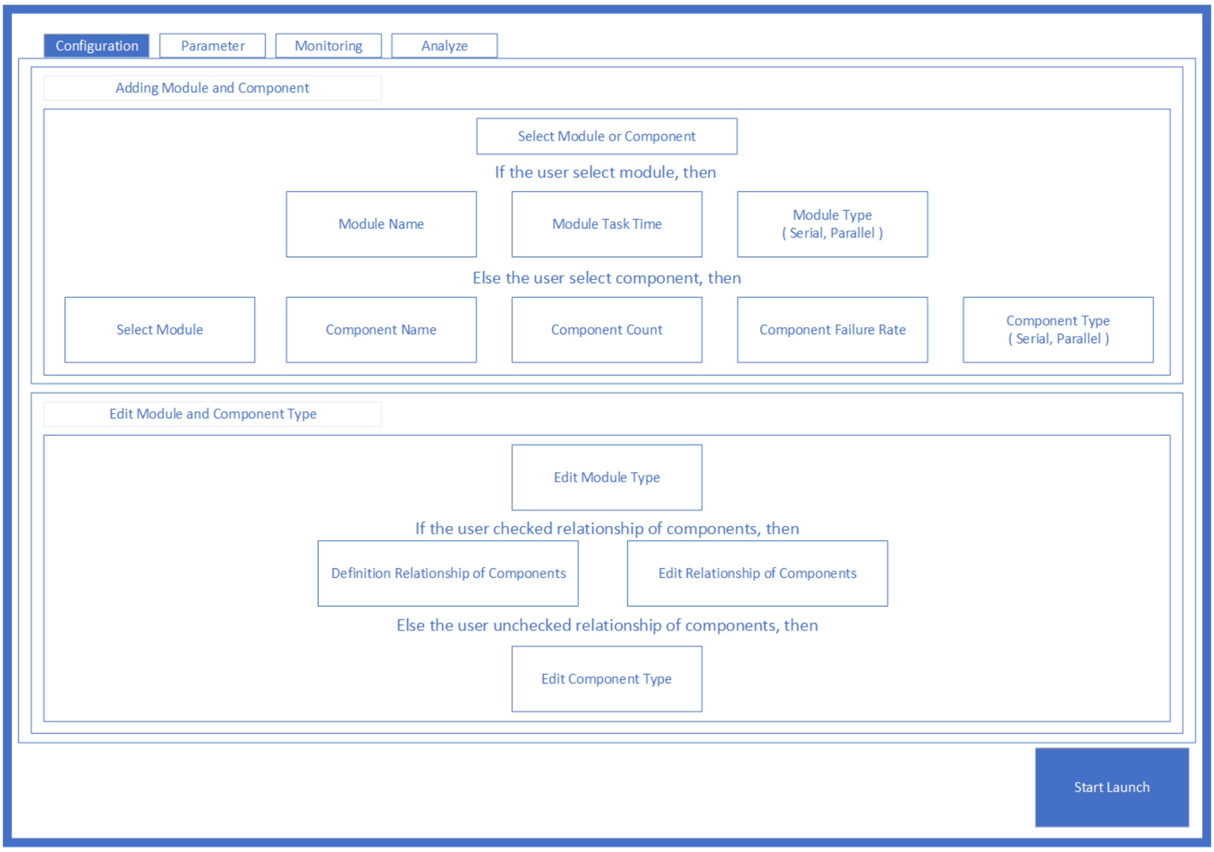

Figure 16: Configuration Tab Interface

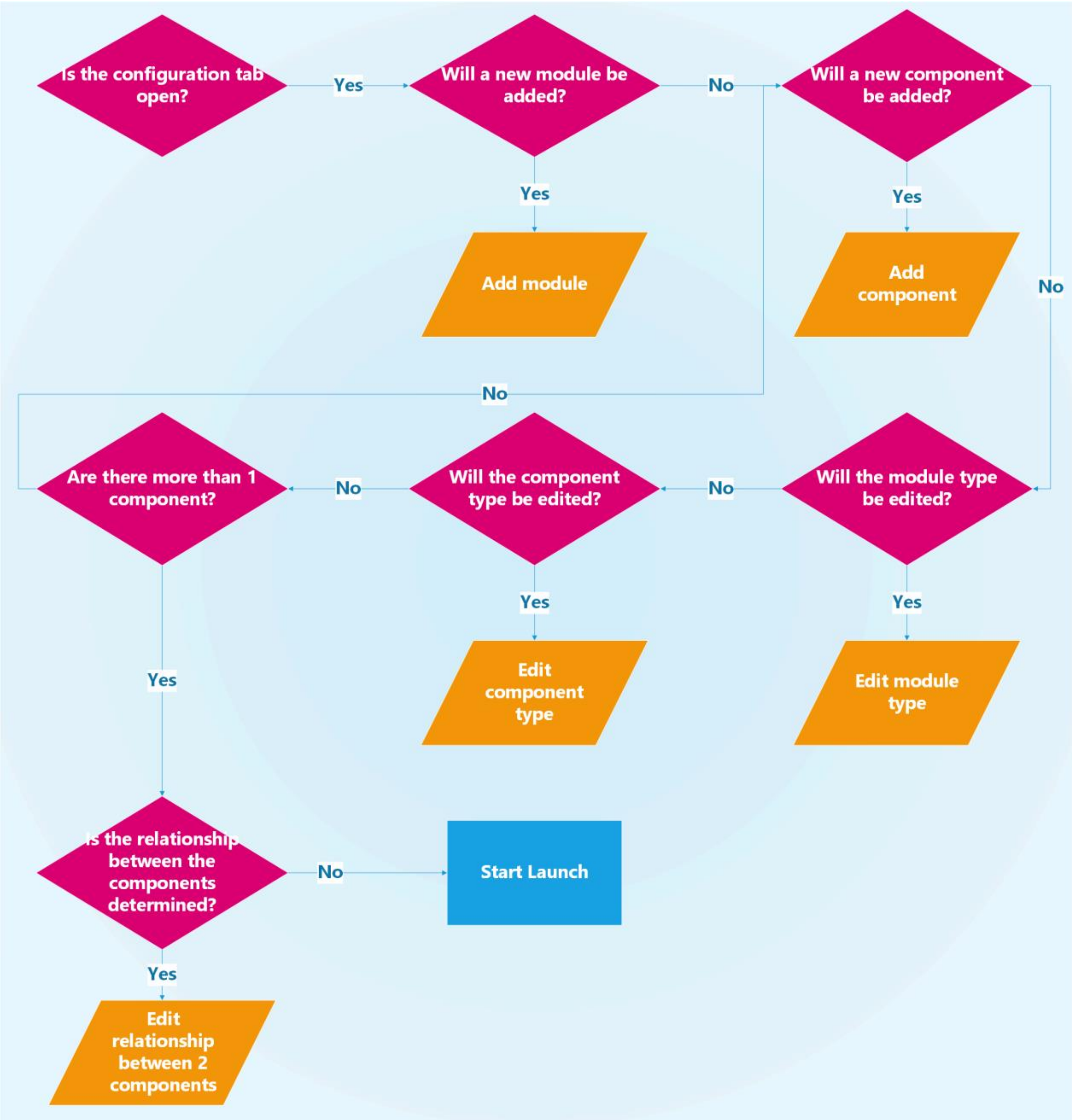

Figure 17: Configuration Tab Flow Diagram Design

8.2.2. Parameter Tab

User can see formulas, other parameters and module and component parameter values added from configuration tab in this section. The parameters entered in the "Module and Component Parameters" section are displayed and can be updated.

In the “Formula” section, the user can calculate the reliability and failure rate values by creating his own custom functions instead of the available functions. In addition, the existing functions can be used together with specially formulated formulas.

In the “Variable” section, the user determines the values of the variables to be used in the formulas which user creates.

In the “Task Time” section, the time values entered from the configuration section are updated.

The “Load and Temperature” section provides temperature and load values for the robot or other system.

The interface and flow diagram design studies of the Parameter Tab are given in Figure 18 – 19.

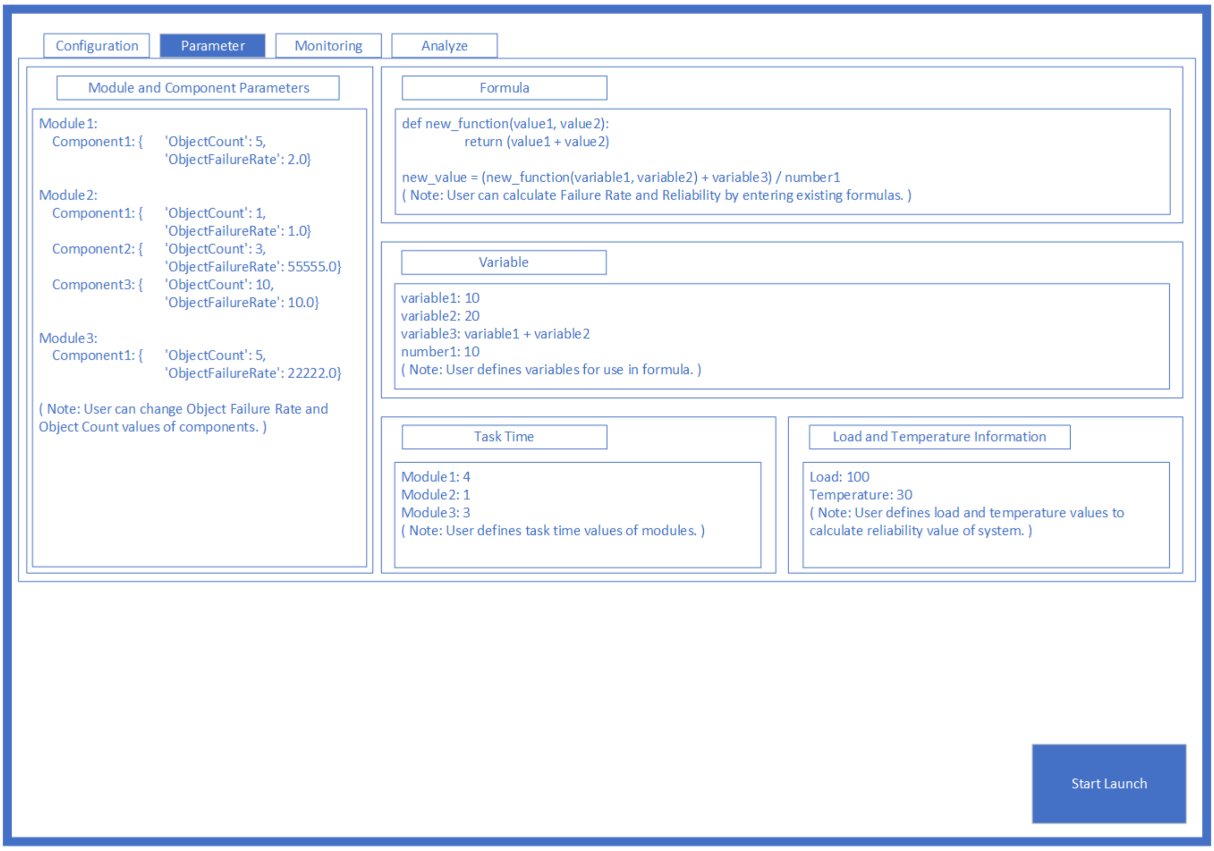

Figure 18: Parameter Tab Interface

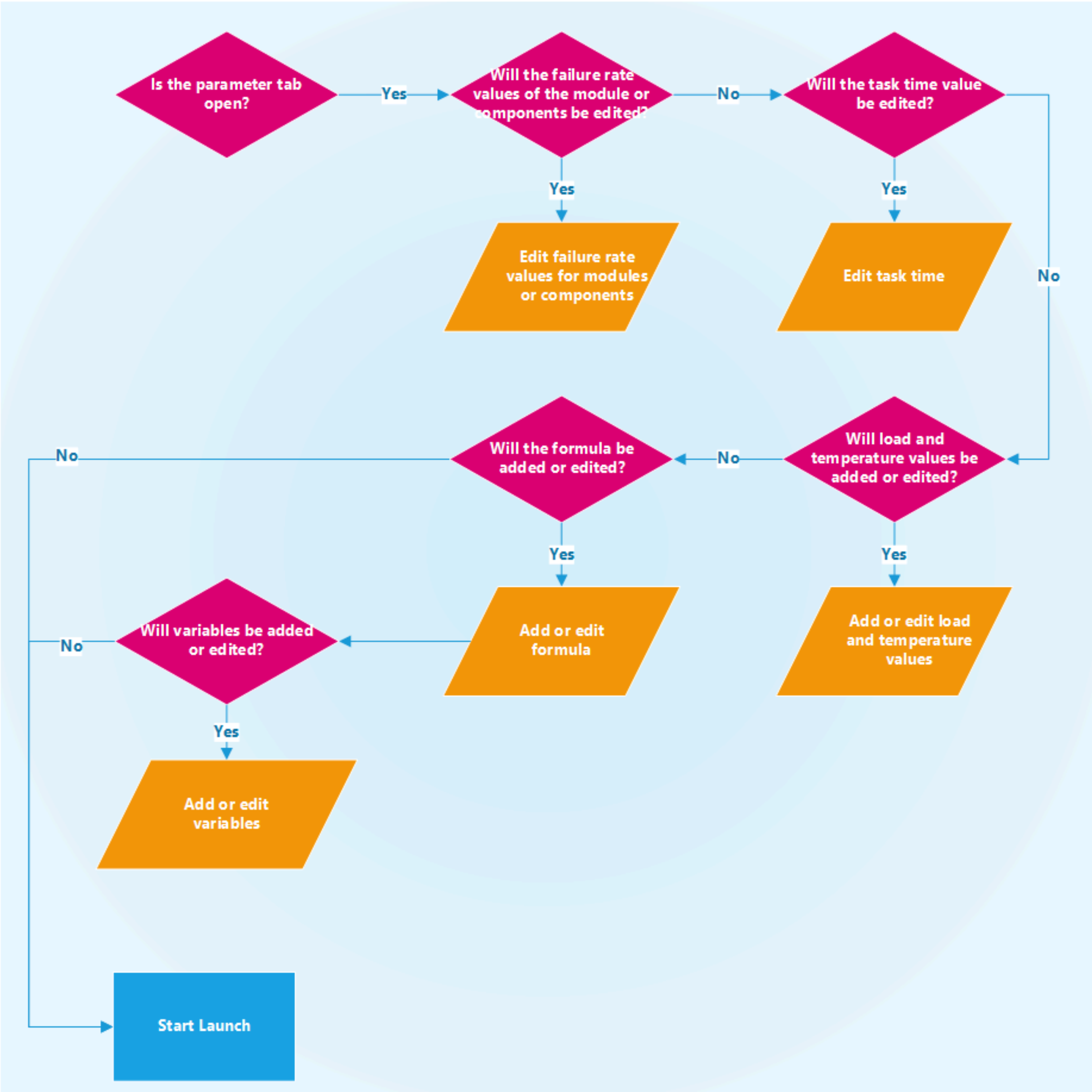

Figure 19: Parameter Tab Flow Diagram Design

8.2.3. Monitoring Tab

If the “Monitoring Object” section is empty when the user first enters the Monitoring Tab, user must first click the start launch button. In addition, if the user has added new modules and components to the system or updated the system, user must click the start launch button to view the current graphs.

The user selects the graph he wants to display from the “Monitoring Object” section and the selected graph is displayed.

The graph shows the reliability and failure rates of the system and module for the system option. In addition, the types of modules are shown. If one of the created modules is selected, reliability, failure rate values and type of the module; failure rate, count and type of component are shown.

Coloring was used to show the type of modules and components in the graphics. Parallel units are shown in green and serial units are shown in orange.

The interface and flow diagram design studies of the Monitoring Tab are given in Figure 20 – 21.

Figure 20: Monitoring Tab Interface

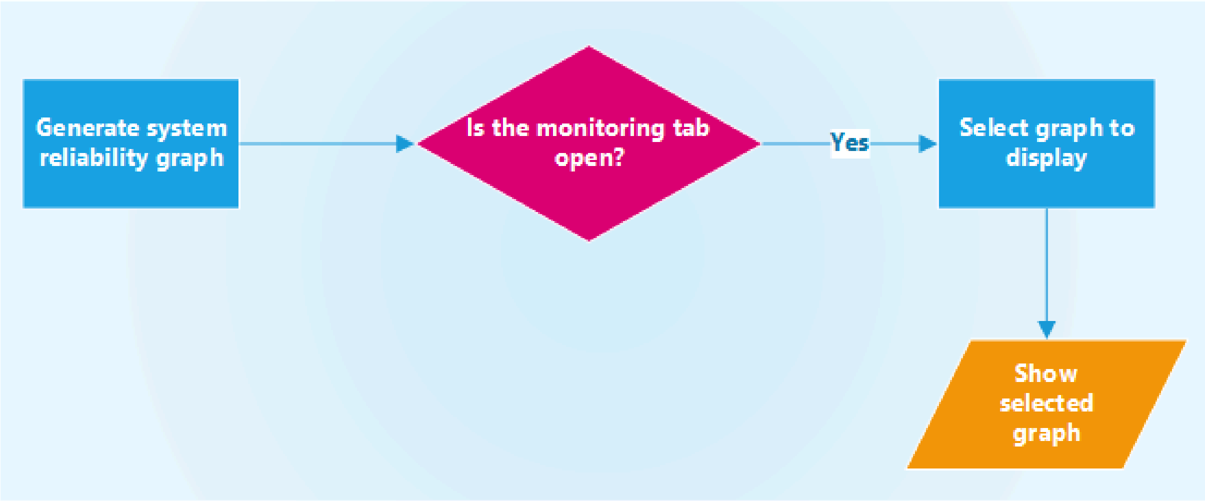

Figure 21: Monitoring Tab Flow Diagram Design

8.2.4. Analyze Tab

If the "Object To Be Analyzed" section is empty when the user first enters the Analyze Tab, user must first click the start launch button.

The user selects the object he wants to analyze from the "Object To Be Analyzed" section and the selected real-time data is displayed as a plot.

The interface and flow diagram design studies of the Analyze Tab are given in Figure 22 – 23.

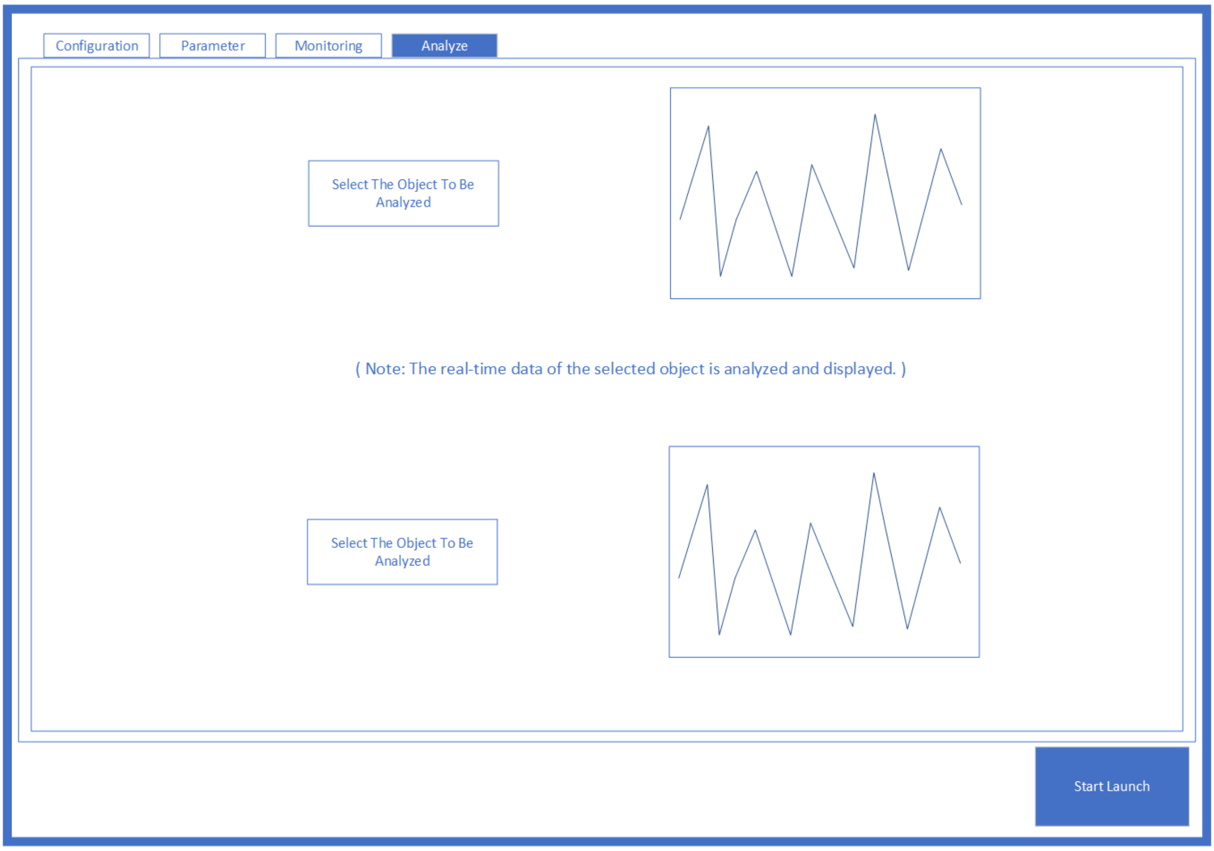

Figure 22: Analyze Tab Interface

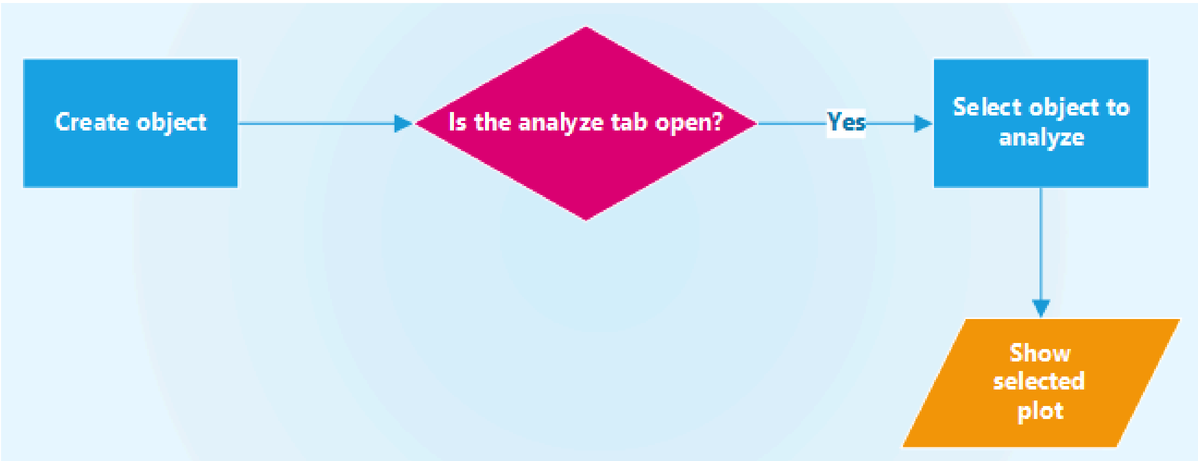

Figure 23: Analyze Tab Flow Diagram Design

8.2.5. Start Launch

When the user adds new modules, components, formulas, variables, parameters or makes any changes on them, user can add this changes to the system by clicking the start launch button. First, the calculation starts with the calculation of the components. Modules are formed by calculating the components in serial or parallel to each other. Then reliability and failure rate values of the module are calculated. After all modules are calculated, failure rate and reliability values of the system are calculated according to the serial and parallel status of the modules. If the user has entered the formula and variable, these operations are primarily calculated on the formulas entered by the user. The results of the modules and the system are calculated. Their serial and parallel relationships are dynamically generated so that they are shown in the graph.

The flow diagram design studies of the Start Launch are given in Figure 24.

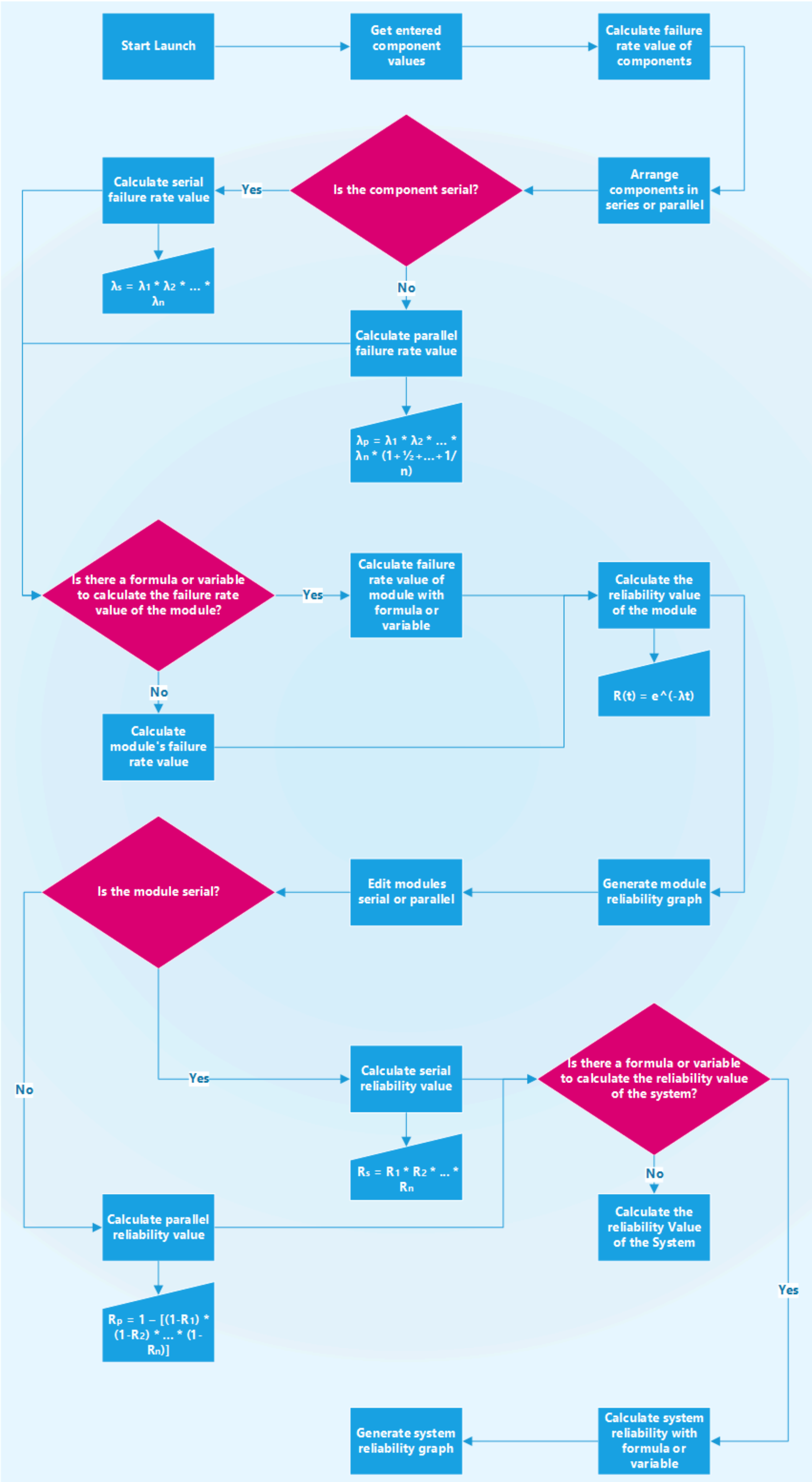

Figure 24: Start Launch Flow Diagram Design

The flow diagram of the system is shown in Figure 25.

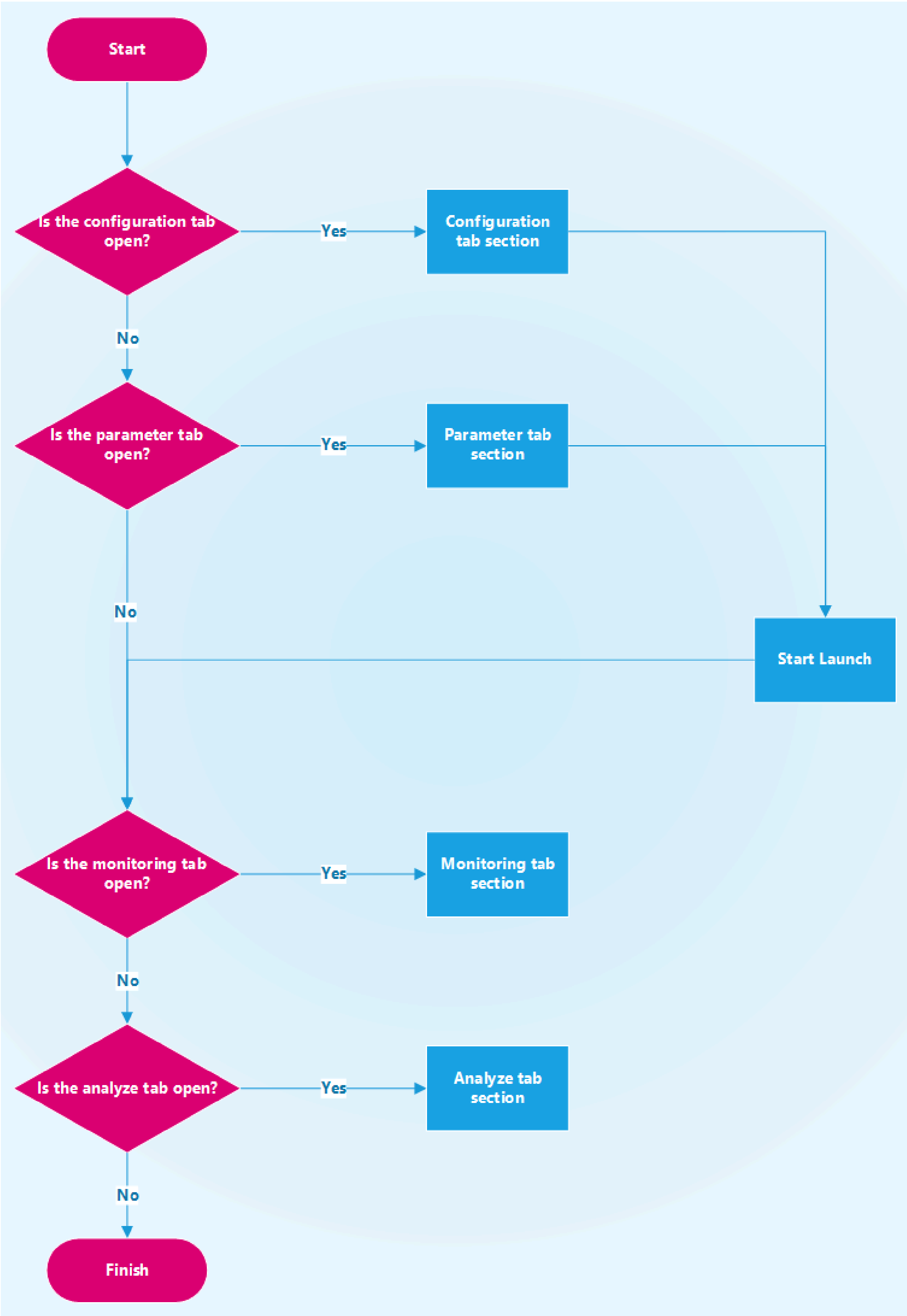

Figure 25: System Flow Diagram Design

8.3. Result

The user can analyze the system and its parts in real time by calculating the reliability and failure rate values of the system which is created with phm tools. The user can also enter his own formulas and variables for special calculations. The entered values can be viewed in the interface and easily updated. In addition, the types and and relationship between created modules and components can be determined by the interface. With the Monitoring feature, the calculated values are displayed by selecting one of the system or module. Modules and components are colored according to their types. The Analyze section shows the real-time graph of the selected object.

9. RESULTS

Nowadays, robots have taken place of human beings in every area so the reliability of the robot has become important. Furthermore, prognostic-aware systems are also used in many systems for sustaining autonomy, lifetime extension, etc. Reliability analysis is applied to improve the reliability and lifetime extension of imperfect robotic systems and to minimize the failures that may be occur in these systems. Overall reliability of the robot is obtained with applying the reliability analysis to all subsystems, components and parts of robot. Using this reliability value, probability of task completion (PoTC) metric is calculated and it shows the succesfullity of our robot in specified task.

In this report, model-based Prognostic and Health Management (PHM) tool for robotic systems is presented. PHM systems should have some features such as advanced diagnosis, predictive prognostic, health reporting, extending lifetime of the system, improve system performance etc. This report includes some equipment informations required for PHM applications. Also in this report, accelerated life test models and life distribution functions are found in order to propose model-based method. Report also includes, hazard rate of mechanical and electrical components that are found in our robot. Using components' hazard rates, reliability of each component calculation is given in this report. In order to find system relability, robot configuraiton setup must be known. In this report, some configurations such as series, parallel, hybrid, k out of n, etc. are given. Finally, you could find calculation of PoTC of the system at specified task in this report.

Three tests are realized at use case scenario section. At the first test, all components' hazard rate is found by using Section 5 at 35 ℃. Using these hazard rates, reliabilities of each component is calculated by using Exponential Distribution function at 1000 hours time interval. Finally, at the first test, system reliability is calculated by using robot configuration. The results show that system reliability depends on the component failure rates and their configurations. At the second test, first test is repeated at various temperature conditions from 25 ℃ to 175 ℃ at 5 ℃ temperature step. Results show that, reliability of the system decreases, when temperautre increases because of the nature of the electrical components. At the final test, system PoTC is calculated at 35 ℃ in specified environment. In this environment, robot follows five segments of the path. This test shows that, PoTC of the system is depends on the distance travelled by robot. When distance increases, robot task completion probability decreases.

In this study, a comprehensive and systematic works of the different reliability models and analytical tools for various systems are given. Furthermore, hazard rate of components, system configuration, reliability, and the probability of task completion of the robot are obtained.

10. REFERENCES

[1] Modarres, M., Kaminskiy, M. P., & Krivtsov, V. (2016). Reliability engineering and risk analysis: a practical guide. CRC press.

[2] Carlson, J., & Murphy, R. R. (2003). Reliability analysis of mobile robots. International Conference on Robotics and Automation (Cat. No. 03CH37422) (Vol. 1, pp. 274-281).

[3] Tortorella, M. (2015). Reliability, maintainability, and supportability: best practices for systems engineers. John Wiley & Sons.

[4] Carlson, J., Murphy, R. R., & Nelson, A. (2004). Follow-up analysis of mobile robot failures. In International Conference on Robotics and Automation, 2004. Proceedings. ICRA'04. 2004 (Vol. 5, pp. 4987-4994).

[5] Lee, J., Wu, F., Zhao, W., Ghaffari, M., Liao, L., & Siegel, D. (2014). Prognostics and health management design for rotary machinery systems—Reviews, methodology and applications. Mechanical systems and signal processing, 42(1-2), 314-334.

[6] Shi, G., Dong, P., Sun, H. Q., Liu, Y., Cheng, Y. J., & Xu, X. Y. (2017). Adaptive control of the shifting process in automatic transmissions. International Journal of Automotive Technology, 18(1), 179-194.

[7] Stancliff, S., Dolan, J. M., & Trebi-Ollennu, A. (2005). Towards a predictive model of robot reliability.

[8] Carlson, J., & Murphy, R. R. (2005). How UGVs physically fail in the field. IEEE Transactions on robotics, 21(3), 423-437.

[9] IEEE Standard 1413.1-2002. (2003). IEEE guide for selecting and using reliability predictions based on IEEE 1413.

[10] Xie, M., Dai, Y. S., & Poh, K. L. (2004). Computing system reliability: models and analysis. Springer Science & Business Media.

[11] Dhillon, B. S. (2006). Maintainability, maintenance, and reliability for engineers. CRC press.

[12] Wasserman, G. (2002). Reliability verification, testing, and analysis in engineering design. CRC Press.

[13] European Power Supply Manufacturers Association. (2004). Guidelines to understanding reliability prediction.

[14] Hoang, P. (2006). Reliability modeling, analysis and optimization (Vol. 9). World Scientific.

[15] Foucher, B., Boullie, J., Meslet, B., & Das, D. (2002). A review of reliability prediction methods for electronic devices. Microelectronics reliability, 42(8), 1155-1162.

[16] Center, N. S. W. (1992). Handbook of reliability prediction procedures for mechanical equipment. Carderock Division, Naval Surface Warfare Center.

[17] H. Wayne Beaty and James L. Kirtley, Jr., Electric Motor Handbook, McGraw-Hill Book Company 1998

[18] IEC 62380 Technical Committee. (2004). Reliability Data Handbook-Universal Model for Reliability Prediction of Electronics Components, PCBs and Equipment. *IEC TR 62380*.

[19] US Department of Defense. (1986). Military Handbook. Reliability Prediction of Electronic Equipment. US Department of Defense.

[20] Failure Rate Estimates for Mechanical Components, Available: https://reliabilityanalyticstoolkit.appspot.com/mechanical_reliability_data_solution, Accessed: 19.07.2019

[21] SICK S300 Expert S30B-3011GB, Online data sheet, Available: https://cdn.sick.com/media/pdf/6/46/846/dataSheet_S30B-3011GB_1057641_en.pdf, Accessed: 19.07.2019

[22] Texas Insturments, Reliability Estimator, Available: http://www.tij.co.jp/quality/docs/estimator.tsp?OPN=LM2596S-12/NOPB&download=download, Accessed: 19.07.2019