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Reliability Prediction of Electronic Navigation and Guidance System Employing High Quality Parts to Achieve Increased Reliability

Ali Peiravi
Department of Electrical Engineering, Ferdowsi University of Mashhad,
Postal Code 9177948974, Mashhad, Iran

Abstract: In this study, the issue of reliability prediction of electronic systems and the various existing databases for part failure rate is addressed first. Then the importance of using high quality parts for the design of reliable electric and electronic systems is stressed. Various parts used in system design are discussed in detail and the way their quality is quantified in reliability studies is thoroughly presented. Reliability modeling is performed and the results of the reliability analysis of the main computer of an electronic navigation and guidance system using parts of various qualities is discussed. The results presented in this study show that the use of high quality parts could be employed as a means of reliability improvement in electronic systems where other viable alternatives for reliability improvement are more difficult or more expensive. These results may also be applied to the reliable design of other high-reliability consumer or military products.

Key words: Quality factor, reliability, failure rate, MTTF, MIL-HDBK-217F

INTRODUCTION

Nowadays reliability requirements for products and systems are constantly rising due to more strict requirements by consumers. Manufacturers who are able to manage reliability of their manufactured products have significant competitive advantages. The most important issue which they face in the early stages of product design and development is reliability prediction in the initial stages of a product's life.

The development of a domain-specific software architecture for intelligent (adaptive) guidance, navigation and control for aerospace applications was discussed by Agrawala *et al.* (1992). In that study, the need to adapt to a variety of specialized target hardware systems, requirements for high reliability and system certification and increasing demands for functional integration and high performance computing were presented. The approach used by Agrawala *et al.* (1992) exhibited three major themes: an extensive reliance on formal models, a provision of multiple views corresponding to multiple areas of skills and requirements and an open toolset and layered architecture. The importance of reliability is stressed by considering the importance of fault tolerance, security, testing and plant model verification. However, their software approach to the problem is not useful in the system under study, since the present system is already operational and no changes in its software or structure is possible.

Reliability improvement or growth is one of the main objectives in any system development effort, especially in sensitive medical equipment, aerospace and military applications. Reliability improvement is an ongoing effort in many industries. One may cite (Braem *et al*., 2008) for example, who model probabilistic connectivity in multi-hop body sensor networks in order to determine ways to improve reliability. Their results for two reliability improvements are given: randomization of the schemes and repeating the schemes received from a parent node. Moreover, Qi *et al.* (2009) present results of experimental work carried out in order to find the reliability of plastic ball grid array packages under various manufacturing and multiple environmental loading conditions. They performed board-level temperature cycling, vibration and combined temperature cycling and vibration testing to quantify reliability and find ways to improve it. Todinov (2009) addressed the issue of reliability improvement in a product using a comparative method for improving the resistance to failure initiated by flaws. The advantage of his proposed method for improving the resistance to failure initiated by flaws is that it does not rely on a Monte Carlo simulation and does not depend on knowledge of the size distribution of the flaws and the material properties.

The aim of this study is to improve the overall reliability of an electronic navigation and guidance system. The use of high reliability parts is employed in order to improve reliability of the main computer of the system since other alternatives were much more expensive to realize. The first step in any reliability improvement program is reliability prediction.

METHODS TO PREDICT RELIABILITY OF ELECTRONIC SYSTEMS

Reliability prediction is concerned with assessing a numeric value for a reliability indicator which is usually either failure rate (λ) or Mean Time To Failure (MTTF), in the initial stages of design and development of a product. Reliability prediction can be carried out using various techniques such as using past experience with similar items, expert's estimates, etc. (Denson and Keene, 1998) presented a reliability assessment methodology for electronic systems whereby an initial reliability prediction was first derived and then a model was used for data fusion or integration of all reliability data. Their model introduced a variance measure into the Mean Time Between Failures (MTBF) prediction.

However, the most credible approach to reliability prediction is utilizing existing international reliability databases and reliability prediction methods. Such reliability databases provide numeric values of reliability indicators for specific type of items. Reliability prediction methods provide, for separate groups of items, models that enable one to take into account specific operating conditions by choosing various factors and allow the calculation of a numeric value for the part's failure rate.

Stresses which parts experience during operation play a vital role in expected lifetime. Klinger *et al.* (1989) has presented a detailed analysis of the way to include the effect of various stresses on the reliability of parts in the AT and T approach. The Arrhenius equation with various excitation energies for various modes of failure are used in this approach. The main difficulty with this approach is the exact value for the excitation energy to be used for each mode of failure.

A simple and most common source for failure rate data is the MIL-HDBK-217F (1995) which was developed by the US Department of Defense. This standard was primarily developed for reliability prediction of military electronic components. Nowadays, the usage of the standard is common in many non-military areas and it is the most widely used reliability prediction method of electronic components. The values included in the standard are based on statistical analysis of actual field failures and are used to calculate failure rates. The standard contains prediction about generic types of electronic components such as microcircuits, semiconductors, tubes, lasers, resistors, capacitors, inductive devices, rotating devices, relays, switches, connectors, interconnection assemblies, meters, quartz crystals, lamps, electronic filters and fuses. It contains two prediction methods, a parts count method and a parts stress method. The parts count method may be used early in the design and development of the product, while the part stress prediction method requires a great amount of detailed information about the various conditions of parts used in the product and is applicable only later when stresses and other environmental and quality factors are known for each component. Other databases were developed later.

One may also refer to the EPRD-97 (1997) database which contains failure rate data on electronic components such as capacitors, diodes, integrated circuits, optoelectronic devices, resistors, thyristors, transformers and transistors. The data included in the database has been gathered from the early 1970's up to 1996 by long-term monitoring of the components in the field with primary emphasis on obtaining data on relatively new component types, different sources, application environments and quality levels. The purpose of this database is to provide failure rate data on commercial quality components to complete the MIL-HDBK-217F (1995) by providing data on the component types not addressed by it. Later on, when data for failure rate of non-electronic parts was needed, the NPRD-95 (1995) was developed using data collected from the early 1970's up to 1994. It contains failure rate data on a wide variety of electrical, electromechanical and mechanical components obtained by long-term monitoring of the components in the field. The data collection was focused on obtaining data on relatively new component types, data on many different sources, application environments and quality levels.

Recently, SPIDR was released in 2006 by the Alion System Reliability Center as an integrated system and parts reliability database. It contains reliability data to replace Non-electronic Part Reliability Data NPRD-95, Electronic Part Reliability Data EPRD-97, Failure Mode and Mechanism Distributions FMD-97 and Electrostatic Discharge Susceptibility Data 1995 VZAP. It contains more than a double amount of data contained in the previous two databases, namely it contains data on more than 6000 electronic, electric, electro-mechanical and mechanical component types. The database is based on nearly 40 years of experience and on the data collection. A similar effort was carried out in other countries to compile failure rate data and reliability prediction techniques. One may cite FIDES which was developed by consortium of French defense and commercial aeronautical companies and published under the supervision of the French Ministry of Defense in 2004. The advantage of FIDES over earlier methods is that it based on the physics of failures method and supported by the analysis of test data, field returns and existing modeling as expressed by Martin and Robert (2005). FIDES was developed using practical failure data from the aeronautical and military area and from manufacturers with the objective of making realistic reliability predictions for electronic equipment, including systems operating in severe environments such as military defense and aeronautics. The method takes into account the failures due to manufacturing, development and stresses related to the application field, e.g., electrical, mechanical and thermal. The method is focused on electric, electronic and electromechanical items including integrated circuits, discrete semiconductors, capacitors, thermistors, resistors, potentiometers, inductors, transformers, relays, printed circuit boards, connectors and piezoelectric parts. The FIDES provides models for components and printed wiring assemblies, considers technological and physical factors, considers the mission profile, considers mechanical and thermal overstresses and considers the failure rates of a specific supplier of a component. Moreover, FIDES takes into account failures linked to development, production, field operation or maintenance processes. As Martin and Robert (2005) concluded the estimates for failure rates provided by the FIDES methodology compares closely to the observed failure rates while the MIL-HDBK 217 predictions are more conservative. However, there is not sufficient studies done using FIDES to support the validity of the FIDES approach and further evaluation of different systems using the FIDES approach is needed in order to verify its consistency and accuracy.

Another difficulty in reliability prediction is rooted in the fact that in actual system reliability prediction, one often needs to rely on several different data sources. Using data from various sources each with differing degrees of estimation uncertainty poses several problems as addressed by Coit and Jin (2001), who proposed to prioritize system-reliability prediction activities and defined a Reliability-Prediction Prioritization Index (RPPI) to rank components based on their potential for improving the accuracy of a system-level reliability prediction by decreasing the variance of the system-reliability estimate. (Coit and Jin, 2001) provided several examples and proposed additional testing or analysis for components with a high RPPI to reduce the variance of the component reliability estimate. This is similar to the sensitivity analysis which is a common approach in reliability studies. Ramirez-Marques and Levitin (2008) proposed an approach for the estimation of reliability confidence bounds based on component reliability and uncertainty data. Their proposed approach is based on universal generating function technique. They showed that this approach is even more effective than pure Monte Carlo simulations due to more precise reliability estimation and less computational effort.

RBD SYSTEM RELIABILITY PREDICTION

One may either use analytic methods for the prediction of system reliability or computer simulations. In this study, the Reliability Block Diagram (RBD) approach was adopted. The system was first studied in detail to discover the way each part affected the reliability of the modules in which it was used and then the role of each module in the reliability of the subsystem was studied. An RBD was developed. Next the failure rate of the system was computed using Excel spreadsheets. The reliability may be computed as follows for series parts as in Eq. 1:

$$R_S(t) = \prod_{i=1}^{n} R_i(t) \qquad (1)$$

Or for n_r redundant parts in parallel, reliability may be computed as in Eq. 2:

$$R_P(t) = 1 - \prod_{i=1}^{n_r} (1 - R_i(t)) \qquad (2)$$

The system was assumed to be operating in its useful period of life where the exponential probability distribution function may be assumed for the reliability of the parts as in Eq. 3.

$$R(t) = e^{-\int \lambda(t).dt} = e^{-\lambda t} \qquad (3)$$

In this study, the failure rate data were mostly obtained from the most common of these data sources, that is MIL-HDBK-217F (1995). Reliability data for parts whose failure rate data were not available in MIL-HDBK-217F were extrapolated from NPRD-95 (1995) to adjust for the conditions in which the system operates.

The failure rate of electric and electronic parts is a function of their quality as well as other factors such as temperature, operating environment and other stresses such as pressure, voltage, etc as in Eq. 4.

$$\lambda = \pi_Q \times f(\pi_T, \pi_E, \pi_S, \ldots) \qquad (4)$$

where, π_Q is the quality factor, π_T, π_E and π_S indicate various other factors which affect the reliability.

In most common databases for failure rate, the basic procedure for calculating the failure rate is by multiplying a base failure rate by operational and environmental stress factors. An example of a semiconductor component's part stress model is as in Eq. 5:

$$\lambda = \lambda_g \times \pi_T \times \pi_A \times \pi_R \times \pi_S \times \pi_C \times \pi_Q \times \pi_E \qquad (5)$$

where, λ_g is the generic base failure rate for the part, π_T is the correction factor to consider the effect of temperature on the failure rate, π_A is the application factor, π_R is the power rating factor, π_S is the power stress factor, π_c is the contact construction factor, π_Q is the quality factor and π_E is the environment factor.

The various operating conditions such as ground, ground mobile, naval, air or missile launch also have an effect on part reliability as shown in Table 1.

Table 1: The various coefficients of operating conditions for various electronic parts

	Environment													
Part type	G_B	G_F	G_M	N_S	N_U	A_{IC}	A_{IF}	A_{UC}	A_{UF}	A_{RW}	S_F	M_F	M_L	C_L
Microcircuits	0.5	2	4	4	6	4	5	5	8	8	0.5	5	12	220
Semicoductor														
Low frequency	1	6	9	9	19	13	29	20	43	24	0.5	14	32	320
High frequency	1	2	5	4	11	4	5	7	12	16	0.5	9	24	250
Optoelectronics	1	2	8	5	12	4	6	6	8	17	0.5	9	24	450
Resistors	1	4	16	12	42	18	23	31	43	63	0.5	37	87	1728
Capacitors	1	10	20	7	15	12	15	25	30	40	0.5	20	50	570
Inductive devices	1	6	12	5	16	6	8	7	9	24	0.5	13	34	610
Synchros and resolvers	1	2	12	7	18	4	6	16	25	26	0.5	14	36	680
Relays														
Mechanical	1	2	15	8	27	7	9	11	12	46	0.5	25	66	N/A
Time delay	1	3	12	6	17	12	19	21	32	23	0.4	12	33	590
Switches	1	3	18	8	29	10	18	13	22	46	0.5	25	67	1200
Circuit breakers	1	2	15	8	27	7	9	11	12	46	0.5	25	66	N/A
Connectors														
General	1	1	8	5	13	3	5	8	12	19	0.5	10	27	490
Sockets	1	3	14	6	18	8	12	11	13	25	0.5	14	36	650
Interconnection assemblies (PTH)	1	2	7	5	13	5	8	16	28	19	0.5	10	27	500
Connection	1	2	7	4	11	4	6	6	8	16	0.5	9	24	420
Meters, panel	1	4	25	12	35	28	42	58	73	60	1.1	60	N/A	N/A
Quartz crystals	1	3	10	6	16	12	17	22	28	23	0.5	13	32	500
Lamps	1	2	3	3	4	4	4	5	6	5	0.7	4	6	27
Electronic filters	1	2	6	4	9	7	9	11	13	11	0.8	7	15	120
Fuses	1	2	8	5	11	9	12	15	18	16	0.9	10	21	230

N/A: Not available

Table 2: The various classes and quality factors for electronic parts per Mil-HDBK-217F (1995)

No.		Description		π_Q
1		Class S categories:		
		(1) Procured in full accordance with MIL-M-38510, class S requirements.		0.25
		(2) Procured in full accordance with MIL-I-38535 and appendix B thereto (Class U).		
		(3) Hybrids: (Procured to class S requirements (quality level K) of MIL-H-38594.		
2		Class B categories:		
		(1) Procured in full accordance with MIL-M-38510, class B requirements.		1.0
		(2) Procured in full accordance with MIL-I-38535, (Class Q).		
		(3) Hybrids: (Procured to class B requirements (quality level H) of MIL-H-38534.		2.0
3		Class B-1 categories: Fully Compliant with all requirements of paragraph 1.2.1 of MIL-STD-883 and procured to a MIL drawing, DESC drawing or other government approved documentation. (Does not include hybrids) for hybrids. use custom screening section below.		
4 (for custom screen test in accordance with MIL-STD-883)	Groups	MIL-STD-883 Screen/Test	Factors	
	1	TM 1010 (temperature cycle, cond B minimum) and TM 2001 (Cconstant acceleration, cond B minimum) and TM 5004 (or 5008 for hybrids) (Final electricals @ temp extremes) and TM 1014 (Seal Test, Cond A, B, or C) and TM 2009 (External visual)	50	2+87/Σfactor
	2	TM 1010 (Temperature cycle, cond B minimum) and TM 2001 (Constant acceleration, cond B minimum), TM 5004 (or 5008 for hybrids) (Final electricals @ temp extremes) and TM 1014 (Seal Test, Cond A, B, or C) and TM 2009 (External visual)	37	
	3	Pre-burn in electricals TM 1015 (Burn-in B-Level /S – Level) an TM 5004 (or 5008 for hybrids) (Post burn-in electricals @ temp extremes)	30 (B evel) 36 (S evel)	
	4	TM 2020 pind (Particle impact noise detection)	11	
	5	TM 5004 (or 5008 for hybrids) (Final electricals @ temp extremes)	11	
	6	TM 2010 / 17 (Internal visual)	7	
	7	TM 1014 (Seal test, cond A, B or C)	7	
	8	TM 2012 (Radiography)	7	
	9	TM 2009 (External visual)	7	
	10	TM 5007/5013 (GaAs) (Water acceptance)	1	
	11	TM 2023 (None- destructive bond pull)	1	
	Examples:			
	(1) Mfg. Performs group 1 test and class B bun-in: $\pi_Q = 2 + \frac{87}{50+30} = 3.1$			
	(2) Mfg. Performs internal visual test, seat test and final electrical test: $\pi_Q = 2 + \frac{87}{7+7+11} = 5.5$			
5	Other commercial or unknown screening levels			10

Table 3: The various classes and quality factors for various semiconductor parts per MIL-HDBK-217F (1995)

		Quality levels				
No.	Part type	JANTXV	JANTX	JAN	Lower	Plastic
1	Non-RF devices/Opto-electronics	0.7	1	2.4	5.5	8
2	High frequency diodes	0.5	1	5.0	25	50
3	Schottky diodes	0.5	1	1.8	2.5	-----
4	RF transistors	0.5	-----	2.0	5.0	-----

Table 4: The various classes and quality factors for resistors and capacitors per MIL-HDBK-217F (1995)

	Resistors						Resistors						
Type	Established reliability style						Established reliability style						
Quality levels	S	R	P	M	MIL-SPEC	Lower	S	R	P	M	L	MIL-SPEC	Lower
π_Q	0.03	0.1	0.3	1.0	3.0	0.3	0.03	0.10	0.30	1.0	3.0	3.0	10

Table 5: The various classes and quality factors for various other devices per MIL-HDBK-217F (1995)

		Quality levels		
No.	Part type	Established reliability	MIL-SPEC	Non-MIL
1	Inductive devices	0.25	1	10
2	Rotating devices	N/A	N/A	N/A
3	Relays, mechanical	0.6	3	9.0
4	Relays, solid state and time delay	N/A	1	4.0
5	Switches, toggle, pushbutton, sensitive	N/A	1	20
6	Switches, rotary water	N/A	1	50
7	Switches, thumbwheel	N/A	1	10
8	Circuit breakers, thermal	N/A	1	8.4
9	Connectors	N/A	1	2.0
10	Interconnection assemblies	N/A	1	2.0
11	Connection	N/A	N/A	N/A
12	Meters, panel	N/A	1	3.4
13	Quartz crystals	N/A	1	2.1
14	Lamps, incandescent	N/A	N/A	N/A
15	Electronic filters	N/A	1	2.9
16	Fuses	N/A	N/A	N/A

N/A: Not available

The quality of the parts being used in the system and the type of part screening also affects the reliability of a system as shown in Table 2.

The effect of quality on semiconductor parts is shown in Table 3.

Table 4 shows the various quality levels used for resistors and capacitors, whereas the effect of quality on other device types is shown in Table 5.

It is easy to see that the failure rates for various parts are vastly dependant on part quality. For example, a low quality resistor has a failure rate that is 333.3% more than one with class S quality, or the failure rate of a plastic high frequency diode is 100 times higher than a JANTXV equivalent.

THE SYSTEM BEING STUDIED

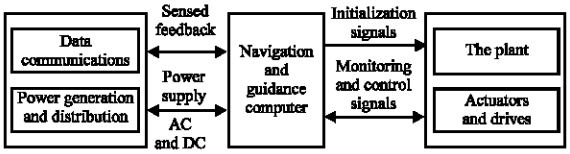

Fig. 1: The various subsystems in the total system

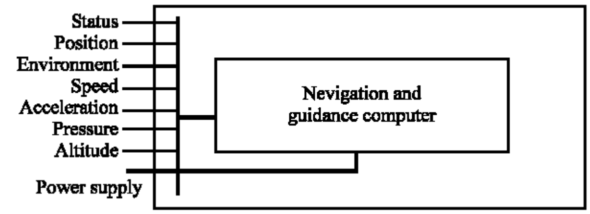

Fig. 2: The navigation and guidance computer subsystem

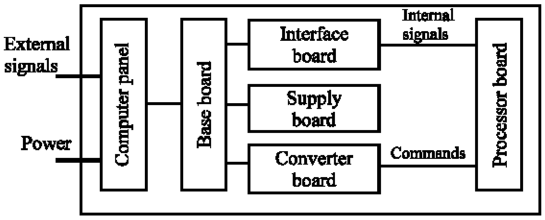

Fig. 3: The physical interconnections between the various subsystems of the navigation and guidance computer

The system under study is only a small portion of the overall system in which there are data communication links, power generation and distribution, navigation and guidance computer, actuators and drives as well as the physical plant itself as shown in Fig. 1.

The subsystem studied in this project is mainly responsible for the navigation and guidance of the vehicle. It also monitors all sensitive devices by receiving their status and issues proper warning signals in case any problems arise. A more detailed description of the navigation and guidance computer is shown in Fig. 2.

This subsystem is itself composed of many smaller units which are briefly shown in Fig. 3. It consists of a digital processor board, an interface board, a converter

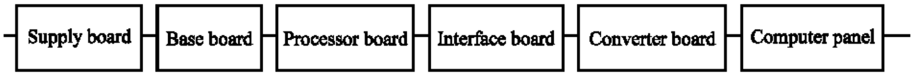

Fig. 4: The reliability block diagram for the navigation and guidance computer

Table 6: The range of the expected failure rate for the various parts used in the main navigation and guidance computer in terms of quality per MIL-HDBK-217F (1995)

Items	Types of component	Maximum	Average	Minimum
1	Integrated circuits	8.520	0.5003	0.082
2	Semiconductors	8.910	1.9320	0.135
3	Resistors	4.243	0.9710	0.201
4	Capacitors	3.233	1.1690	0.163
5	Connectors	1.644	0.3828	0.190
6	Printed circuit boards	13.363	5.2435	0.1517
7	Inductors and transformers	1.400	0.7830	0.1660
8	Other miscellaneous parts	4.700	0.1921	0.00027

Table 7: A part count summary of the various electronic parts and their average failure rates under different operating conditions per MIL-HDBK-217F (1995)

Items	Types of item	Quantity of item	λ_{GB}	λ_{GM}	λ_{AIC}	λ_{ARW}	λ_{MI}
1	Microcircuits	246	0.063	0.500	0.500	1.006	1.512
2	Semiconductors	70	0.215	1.932	2.795	5.160	6.880
3	Resistors	228	0.061	0.971	1.098	3.823	5.280
4	Capacitors	316	0.020	0.396	0.238	0.792	0.990
5	Connectors	34	0.048	0.383	0.144	0.910	1.293
6	PCB Boards	10	0.749	5.244	3.745	14.234	20.227
7	Inductive devices	16	0.065	0.783	0.390	1.566	2.216

board, a power supply board, a base board and a panel which is used to provide the interface between the system and the operator. The electrical schematics and the wiring tables are not needed here, even though they were studied to see how each subsystem's functioning affected the overall system's function in order to determine the reliability block diagram of each board, each subsystem and the overall system.

The navigation and guidance computer was studied in detail to establish the functional role of its various subsystems on its overall functionality and its reliability block diagram is shown in Fig. 4.

In this study, the effect of part quality is taken into consideration by indicating the minimum, average and maximum failure rate for parts used in the system as shown in Table 6.

The components making up the various modules of the system have been shown in Table 7.

The expected minimum, average and maximum failure rates for the parts making up the system may be computed using the part count approach per MIL-HDBK-217F (1995) as shown in Table 8. The quality of the parts used in the existing system have also been recorded in the table showing that an improvement in reliability may be gained by employing high quality parts in the various subsystems of the navigation and guidance computer.

Table 8: The failure rate for the various modules of the main navigation and control computer in Failures per million hours

		Quality factor			
No.	Modules	Existing π_O	π_Q = Minimum	π_Q = Medium	π_Q = Maximum
1	Processor board	81.3739	4.8989	17.2728	104.1563
2	Interface board	34.015	2.2962	18.9517	69.7535
3	Converter board	84.0891	2.3355	20.2722	86.2431
4	Power supply board	164.1522	11.0751	67.4139	461.3059
5	Base board	21.3424	5.2292	9.2781	46.8450
6	Panel	21.6618	17.7173	18.1398	21.9128

Table 9: Failure rate and the MTTF of the navigation and guidance computer for various part qualities

	Quality factor			
Modules	Existing π_O	π_Q = Minimum	π_Q = Medium	π_Q = Maximum
Failure rate (Failures per million hours)	406.6344	43.5502	151.3206	788.2256
MTTF (h)	2459.20	22962.00	6608.5	1268.7

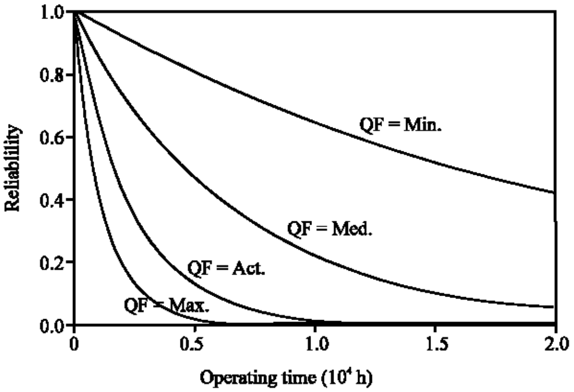

Fig. 5: Reliability as a function of operating time indicating substantial improvement in reliability using better higher quality parts

The total failure rate and MTTF of the navigation and guidance computer is computed using the obtained data and is shown in Table 9.

The system failure rate may be drastically reduced using high quality parts. The information shown in Table 9 shows that one may gain a factor of 18.1 times improvement in MTTF using high quality parts instead of low quality parts. The system reliability is also computed and plotted in Fig. 5 indicating a drastic reliability improvement using higher quality parts even with medium quality with QF = med and even more reliability improvement using very high quality parts with QF = min.

CONCLUSIONS

Since, quality of the parts used in the design of a system play a vital role in the overall reliability of that system, it is important to adopt ways to quantify the effect of part quality on reliability. Standards used for this purpose were reviewed and the MIL-217F approach for the quantification of the effect of quality of parts of system reliability was adopted in this study. The reliability of the computer system of navigation and guidance system was modeled and its reliability prediction was performed.

The use of high quality parts to increase the reliability of an electronic navigation and guidance system was shown to be very effective in this system where we could neither rely upon integration of parts, derating or increased stress testing. A substantial gain in reliability was achieved when assuming the use of parts with high quality. Of course, this comes at a price to be paid for in sensitive or military applications.

The results presented in this study were obtained using Excel spreadsheets and Borland C++ programming on an IBM PC with a 2.8 GHz Celeron Processor. Finally, it is suggested that a new standard be developed for the quantification of the reliability of parts in the developing countries either through grants from the UNESCO, the non-aligned nations or the Islamic nations for the development of products in these countries.

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