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Redundancy for Reliability Growth of Electronic Systems under Various Operating Conditions

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Abstract: Reliability analysis of sophisticated electronic systems is usually performed based on the most common approaches available, namely the state space approach and the Reliability Block Diagram (RBD) approach. The expected operating conditions of the system also play an important role in the analysis of the reliability of the system since they affect its mean lifetime. In this study, redundancy is proposed as a means of reliability growth in the absence of other possible means to achieve this goal. To show this in the form of a case study, state space and RBD reliability modeling are used for the analysis of the reliability of a specific navigation and guidance system in various operating conditions. The growth in reliability is indicated by designing in redundancy and the reliability of the system is shown to be effectively improved where none of the other viable measures are available to us. Measures of reliability such as MTTF, MTTR and availability are estimated under various system operating conditions.

Key words: Mean time to failure, mean time to repair, availability, RBD, state space, redundancy

INTRODUCTION

Analysis of system reliability in both Europe and the United States is as old as the 1940s when the main thrust was behind aerospace applications with severe operating conditions and life-threatening missions. Such studies were later applied to other areas. However, they still remain the most important subject in sensitive applications like military, aerospace and life-critical medical electronics. An early study considering reliability issues in navigation systems dates back to 1966 where a reliability analysis was performed on the Navigation and Flight Instruments subsystem of the Boeing B-2707. Lyngaas and Watson (1966) reported a study that was aimed at determining whether the reliability goals could be met or not and identifying the hardware or human factors which are expected to pose reliability problems. Rogge (1974) reported a study of the reliability of Inertial Navigation System (INS) reliability. He considered the effect of flying hours programs on MTBF and showed that the Time Between Overhaul (TBO) is the best measurement of INS reliability for the TRC.

Agrawala *et al.* (1992) reported the development of a domain-specific software architecture for intelligent (adaptive) guidance, navigation and control for aerospace applications. In their 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) exhibits 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 was stressed in this study 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 in this paper, since the present system is already operational and no changes in its software or structure are possible, except for the use of hardware redundancy.

Boyd and Bavuso (1992) reported the use of reliability modelling and simulation to evaluate the reliability of a hypercube multiprocessor architecture for guidance, navigation and control systems for long duration manned spacecraft. They used simulation to evaluate homogeneous Markovian, non-homogeneous Markovian and non-Markovian models of the hypercube by focusing on the effect of assuming Weibull decreasing component failure rates compared to the usual assumption of constant component failure rates. They also studied the effect of the use of cold spares on system reliability under the assumption of both constant and Weibull decreasing failure rates.

Goodchild (1993) reported the operation of a system that will estimate either the local-relative or absolute-global position of Unmanned Underwater Vehicles

(UUVs). The Seastar system which was presented by Goodchild (1993) allowed for both autonomous and remote controlled navigation of UUVs. However, its configuration is such that it lacks any redundancy and is thereby not very reliable. There is a single navigation computer in their system. Its output is used for three UUV functions, namely the Autonomous UUV Control, including autopilot, attitude and heading and area navigation; guidance and navigation data for acoustic link transmissions to the sea surface segment for UUV monitoring and remote control and guidance and navigation monitoring data for sea surface operations during deployment and recovery. They only rely on duplicate communication links between the UUV and command and control vessel using a direct acoustic link as well as acoustic/radio links by the buoys.

One possible approach to reliability improvement is integration of parts into more modern components with a higher reliability. Integration of discrete parts using modern VLSI gates such as FPAAs and FPGAs are presented as a means of improving system reliability by Peiravi (2008). The improvement in reliability can also be achieved by other means such as accelerated life testing, derating of parts as shown by Peiravi (2009) and use of redundancy in design. The present study stresses the effect of the use of redundancy in design in order to improve reliability where the use of other viable alternative approaches is not feasible.

THE CASE STUDY SYSTEM

The case study system in this research that is subject to reliability growth program is mainly responsible for navigation and guidance and monitors all sensitive devices by receiving their status and issues proper warning signals to the operator in case any problems arise. The initial system was composed of a single navigation and guidance computer as shown in Fig. 1.

In order to improve the reliability different measures could be adopted. Reliability could be improved by using more reliable parts on the system. However, since this product is already a highly reliable product, it used high quality parts to begin with and it was not possible to improve its reliability by using more reliable parts. Another option is to integrate several parts into a single more reliable part. This was also out of the question for the present system since the system already used modern VLSI components which are highly integrated. The next viable option to improve the reliability of the system was derating of parts. However, this was only feasible in a small portion of the system, more specifically in its panel, the power supply and the interface board. Still this could

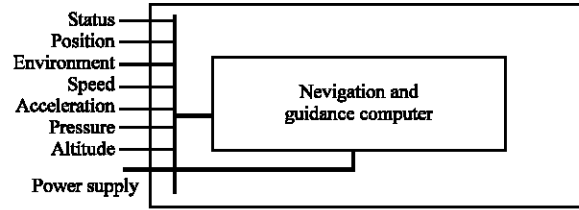


Fig. 1: The initial navigation and guidance system without redundancy

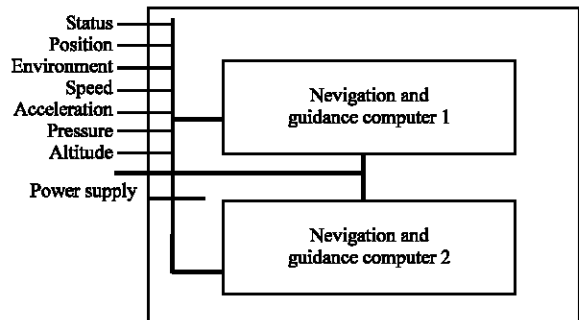


Fig. 2: Navigation and guidance system with redundancy

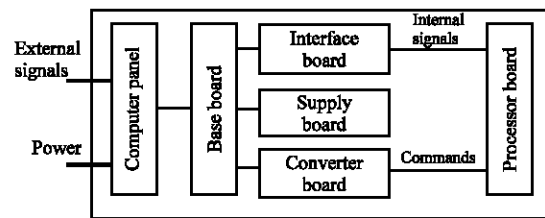


Fig. 3: The interconnections between the various subsystems of the navigation and guidance computer

not bring about the required reliability improvement that was desired. Therefore, the last alternative for reliability improvement being the use of redundancy was chosen in this study. The use of two navigation and guidance computers instead of one was proposed in order to improve the reliability. Therefore, the navigation and guidance computer in the system was doubled up as shown in Fig. 2. The type of redundancy used is active in that once one computer fails, the other may be substituted automatically to take over its functions.

The various subsystems of the navigation and guidance computer are briefly shown in Fig. 3. It consists of a digital processor board, an interface board, a converter 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 in detail in order to see how each subsystem's functioning affected the overall system's function to determine the reliability block diagram of each board, each subsystem and the overall system.

MEASURES OF RELIABILITY

The lifetime of a component is a stochastic variable which is often used in reliability studies. Certain operations on the probability distribution function of this stochastic variable may be used as measures of reliability. The mean time to failure or MTTF is the average time that a given part operates before it fails. It may be computed from the probability distribution function of time to failure f_{T_v} as follows:

$$MTTF = \int_0^{\infty} t f_{T_v}(t) dt = \frac{1}{\lambda}$$

The mean time to repair or MTTR is the average time that a given part is in the failed state before it is repaired and brought back into service. It may be computed from the probability distribution function of time to failure f_{T_r} as follows:

$$MTTR = \int_0^{\infty} t f_{T_r}(t) dt = \frac{1}{\mu}$$

The mean time between failures or MTBF is the average cycle time for a part to operate before it fails and be repaired after it fails and be brought back into service. It may be computed from the MTTF and the MTTR as follows:

$$MTBF = E[T_v + T_r] = MTTF + MTTR$$

The failure rate $\lambda(t)$ and the repair rate $\mu(t)$ are each defined as follows:

$$\lambda(t) = \lim_{\Delta t \rightarrow 0} \frac{1}{\Delta t} P[\text{System down in } (t, t + \Delta t) | \text{System up at } t] = \lambda = \frac{1}{MTTF}$$

$$\mu(t) = \lim_{\Delta t \rightarrow 0} \frac{1}{\Delta t} P[\text{System up in } (t, t + \Delta t) | \text{System down at } t] = \mu = \frac{1}{MTTR}$$

And the reliability of the system may be found from the failure rate function as follows:

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

The probability of failure is the same as unreliability and may be computed from the following:

$$Q(t) = 1 - R(t) = 1 - e^{-\lambda t}$$

System availability gives the probability that the system would perform its expected function at an unknown time t in the future for a repairable system and it may be computed as follows:

$$A = \frac{MTTF}{MTTF + MTTR} = \frac{MTTF}{MTBF}$$

whereas, unavailability is given as:

$$\bar{A} = 1 - A = \frac{MTTR}{MTBF}$$

THE FAILURE RATE AND THE EFFECT OF OPERATING CONDITIONS

The failure rate of electronic parts depends on many factors and is usually shown in the following general form:

$$\lambda = \pi_E \times f(\pi_T, \pi_Q, \pi_S, \dots)$$

where, π_E denotes an application environment coefficient, f denotes a function of, π_T denotes a temperature coefficient, π_Q denotes a quality factor coefficient and π_S denotes a stress coefficient.

For various parts, there are various coefficients to be used and there may be more factors which influence the failure rate of a device. Reliability data can be obtained from various organizations which maintain and provide such data as shown in Table 1.

The application environment coefficient denoted by π_E refers to the expected operating conditions of the system under study. There are certain generic classifications of expected operating conditions which are normally used to calculate an estimate of the failure rate. These operating conditions are classified in various ways by different organizations. Table 2 shows the classifications used by the Department of Defense as per

Table 1: The various sources for failure rate data

Reliability document	Name of organization
MIL-HDBK-217F	Department of Defense of USA
RPP	Bell Laboratory
EPRD	Reliability Analysis Center (USA)
HRD4	British Telecommunication System
CNET	French National Center for Telecommunication Studies
299B	Chinese Standard

Table 2: The generic operating conditions per mil-handbk-217F

Notations	Operating environment
G_B	Ground, benign
G_F	Ground, fixed
G_M	Ground, mobile
N_S	Naval, sheltered
N_U	Naval, unsheltered
A_{IC}	Airborne, inhabited, cargo
A_{IF}	Airborne, inhabited, fighter
A_{UC}	Airborne, uninhabited, cargo
A_{UF}	Airborne, uninhabited, fighter
A_{RW}	Airborne, rotary, winged
S_F	Space, flight
M_F	Missile, flight
M_L	Missile, launch
C_L	Cannon, launch

Table 3: The various coefficients of operating conditions for various electronic parts

Part type	Environment													
	GB	GF	GM	NS	NU	AIC	AIF	AUC	AUF	ARW	SF	MF	ML	CL
Microcircuits	0.5	2	4	4	6	4	5	5	8	8	0.5	5	12	220
Semiconductor														
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

MIL-HDBK-217F (1995). The various coefficients of operating conditions for various electronic parts are shown in Table 3.

MODELING AND SIMULATION

One may use various reported techniques in any reliability study. In this study, the reliability has been estimated using RBD and state space approach, repairability has been studied using Monte Carlo simulations and availability has been studied using the state space approach. The failure rate of the system was estimated using the RBD approach and then the reliability was computed. The reliability block diagram for each navigation and guidance computer is shown in Fig. 4. In a given series system, the failure rate of the system may be computed from the failure rate of the individual parts making up that system as follows:

$$\lambda_s = \sum_{i=1}^n \lambda_i(t)$$

The failure rate may be computed by using a spreadsheet for the navigation and guidance system with redundancy. Then the reliability may be computed as follows:

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

Reliability prediction in the initial stages of product life is an important issue. One has to rely on some existing data bases such as EPRD, NPRD, MIL-217F, etc. This issue is addressed in Vintr (2007), where internationally accepted and the most common tools in the field of reliability prediction such as EPRD-97, NPRD-95, SPIDR™ and the reliability prediction methods MIL-HDBK-217F,



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

PRISM®, FIDES, 217Plus™, RDF 2000, Telcordia SR-332, GJB/z 299B, NSW-98/LE1 are discussed. In this study, the failure rate data were obtained from the most common of these data sources such as MIL-HDBK-217F (1995) or EPRD.

The equivalent part for n_r redundant parts in parallel is computed as follows:

$$R_p(t) = 1 - \prod_{i=1}^{n_r} (1 - R_i(t))$$

THE STATE SPACE MODEL OF THE SYSTEM

The inclusion of a redundant computer in the navigation and guidance system improves the reliability of the system. The state space model of the navigation and guidance system with redundancy is shown in Fig. 5a assuming the possibility of repair after both computers fail and is shown in Fig. 5b assuming that it is not possible to repair the second one after both fail (as it may be the case in some scenarios).

The state space model can be solved using the following equations:

$$\dot{p}(t) = p(t)A$$

$$\sum_{i=1}^3 p_i(t) = 1.0$$

where, $p(t)$ is a row vector indicating the state probabilities, p_0, p_1, p_2 . The matrix A is formed using the transition rates shown in Fig. 5a and b.

This system is solved and the resulting probabilities may be used to find the reliability measures. In either case, the probability of system success is the same as the probability of the first state, or p_0 . The mean time to failure is as follows:

$$MTTF_s = \frac{1}{\lambda_s} = \frac{(3\lambda_c + \mu_c)}{3\lambda_c^2}$$

The system availability is as follows:

$$A_s = \frac{\mu_c(\mu_c + 2\lambda_c)}{\mu_c^2 + 2\lambda_c(\mu_c + \lambda_c)}$$

And the system reliability is as follows:

$$R_s(t) = e^{-\frac{3\lambda_c^2}{(3\lambda_c + \mu_c)}t}$$

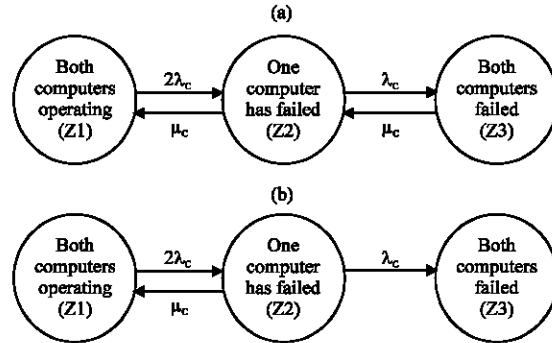


Fig. 5: The state space diagram of the proposed system assuming (a) repair after both fail and (b) no repair after both fail

Table 4: A summary of various electronic parts, their quantity and their average failure rates under different operating conditions

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

Table 5: The overall estimated failure rates for the various subsystems of the navigation and guidance computer in failures per million hours without using redundancy

Subsystems	Operating conditions				
	G_B	G_M	A_{IC}	A_{RW}	M_L
Processor board	8.858	80.779	75.054	195.461	279.2550
Interface board	3.063	32.833	25.523	77.253	106.2490
Converter board	5.714	59.152	58.886	160.607	226.2520
Power supply board	13.88	159.777	182.410	469.236	637.4410
Base board	1.878	26.668	21.626	80.223	109.0000
Panel	1.928	21.177	20.324	49.765	71.0585

The system reliability is computed for five different operating conditions of ground benign G_B , ground mobile G_M , airborne, inhabited, cargo, A_{IC} , airborne, rotary, winged, A_{RW} and missile launch, M_L . The overall estimated failure rates for the various subsystems of the navigation and guidance computer in failures per million hours are shown in Table 5. As shown in Table 5, it can be seen that the failure rates are much higher in more severe operating conditions. Table 6 shows the failure rate and MTTC for one navigation and guidance computer while Table 7 shows the reliability measures for the navigation and guidance system considering various operating environments without using redundancy.

The mean time to repair MTTR for the navigation and guidance computer is:

Table 6: The failure rate and MTTC for one navigation and guidance computer

Reliability measure	Operating conditions				
	G_B	G_M	A_{IC}	A_{RW}	M_L
Failure rate (Failure/ 10^4 h)	35.317	380.386	383.827	1032.545	1429.256
MTTF _c (h)	28314.98	2628.91	2605.34	968.48	699.66
\bar{A}_c (%)	0.00101194	0.01089812	0.0109967	0.02957709	0.0409364

Table 7: Reliability measures for the navigation and guidance system considering various operating environments without using redundancy

Navigation and flight control systems	Operating environment				
	G_B	G_M	A_{IC}	A_{RW}	M_L
λ_s (Failure/ 10^4 h)	0.008706	1.009961	1.028316	7.441721	14.258554
MTTF _s (h)	114862156.74	990137.54	972464.00	134377.51	70133.34
\bar{A}_c (%)	0.00000025	0.00002894	0.0000295	0.00021323	0.0004085

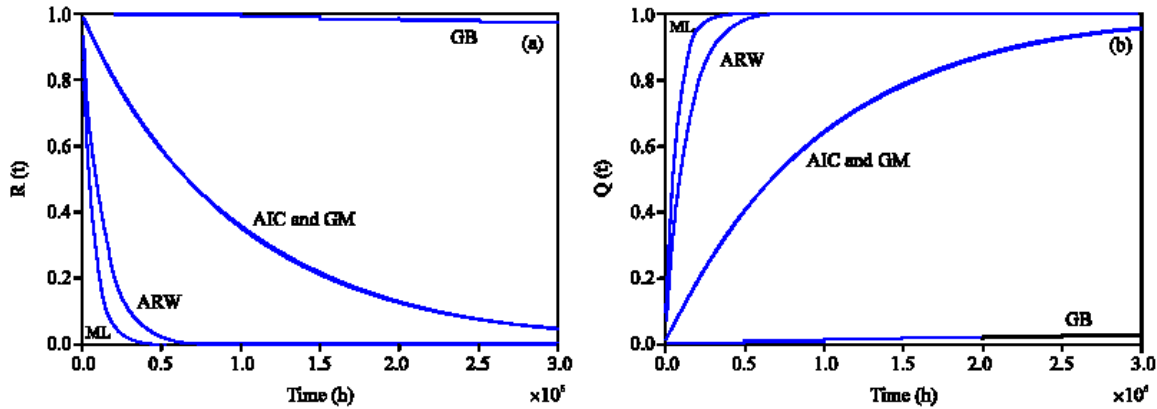


Fig. 6: (a) Reliability R(t) and (b) Failure probability of the navigation and guidance control system for various operating conditions without using redundancy

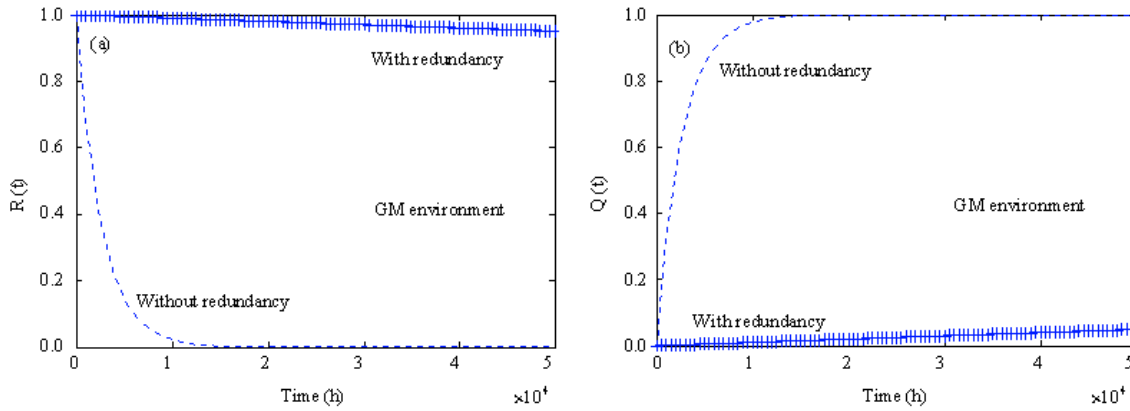


Fig. 7: The effect of using a redundant computer in the navigation and guidance control system, (a) shows the reliability while and (b) shows the failure probability

$$MTTR_c = \frac{1}{\mu_c} = 3.940 \text{ (h)}$$

$$R_c(t) = 1 - Q_c(t) = \text{Exp}(-0.00038327t)$$

The reliability of the navigation and guidance computer may be found using the mean time to failure shown in the Table 4-7. For example, the reliability under A_{IC} operating conditions is as follows:

The reliability and the failure probability of the original navigation and guidance system without redundancy and the proposed redundant system are shown in Fig. 6a and b for 3000000 h of operation.

The effect of using a redundant computer in the navigation and guidance system on the reliability improvement and reduction of the failure probability in ground mobile conditions can be easily shown from Fig. 7. As one may show from Fig. 7a, the reliability of this system after 5000 h of operation is 81.5% more than the case where there is no redundant computer used in the system. Figure 7b shows that the probability of failure is also improved drastically using a redundant flight computer.

CONCLUSION

Expected operating conditions are very important in the analysis of the reliability of navigation and guidance systems. The availability of such systems depends upon their MTTF and MTTR. Therefore, a modular design which helps reduce the repair time is very important in improving the reliability of the whole system. The inclusion of redundancy in design is very effective in reliability improvement, especially in sophisticated equipment where not much else can be done to improve system reliability.

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