Redundancy and Reliability of Air to Air Missile Fuze Electronics

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Abstract: Achieving a high level of reliability is of utmost importance in military applications. A given military grade part is extremely more expensive than its commercial counterpart. This great price difference is mainly due to the differences in design, manufacturing and the quality of parts used in commercial versus military products. Moreover, design of military grade products is much more difficult than commercial or industrial grade products mainly due to the fact that extremely difficult operating environments are expected for military products for which they must be designed, tested and qualified. The achievement of a high level of reliability in military products is also partly due to especial design considerations such as derating of parts, use of high reliability parts, and designing in reliability by the use of redundancy. In this paper, the analysis and design of military products and the ways to increase their reliability are addressed. The specific characteristics of military grade products, the various approaches to designing in reliability and the importance of redundancy especially in military systems are discussed. In this study, the failure rate and mean time to failure of air to air missile fuze electronics that incorporates redundancy are calculated based on MIL-HDBK-217F. [Journal of American Science 2010;6(2):147-154]. (ISSN: 1545-1003).

Key words: Reliability, redundancy, MTTR, MTTF, availability, maintainability

1. Introduction

Reliability requirements for military products and systems are arising due to harsher battle environments as a result of globalization and the appearance of newer global threats. Manufacturers of military products who can design in reliability and are able to manage the reliability growth of their products have a significant competitive advantage over their competitors. Reliability of a given product is seriously affected by the design process.

Reliability improvement or growth is one of the main objectives in any system development effort, especially in sensitive medical equipment, aerospace and military applications. One may cite Braem et al. [1] 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. Todinov [2] 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 their 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 distribution of the flaws and the material properties.

However, the designers must design a product that not only meets its mission's functional requirements, but is also able to perform well under a variety of extremely difficult operating conditions. Even the conditions of storage, transportation before deployment and environmental conditions during deployment must all be included in the design of the product. The design process usually starts with a feasibility study. Usually an initial prototype is designed and built with only 10 to 30 percent the final expected reliability of the product. Engineers and technicians sometimes use an iterative design/test/modify/redesign cycle to improve a product and its reliability. An initial reliability estimate may be performed at the design stage based on a part count analysis of the product to get an idea about the generic MTTF of the product. However, achieving the desired reliability in practice is a great challenge.

Tian et al. [3] presented an approach for joint reliability-redundancy optimization of multi-state series-parallel systems which not only determined the optimal redundancy level for each parallel subsystem, but also aims at finding the optimal values for the variables that affect the component state distributions in each subsystem.

Another form of redundancy in design that may be used to improve reliability is N-modular redundant architecture. Flammini et al. [4] presented a combined failure model for voting architectures based on Bayesian networks and a maintenance model based on continuous time Markov chains in order to analyze the impact of imperfect maintenance on the system safety in safety-critical control systems based on N-modular redundant architectures, using majority voters on the outputs of independent computation units.

Dai and Levitin [5] proposed an algorithm to optimize level of service reliability by utilizing redundancy in execution units in a grid computing system in which the resource management system (RMS) divides service tasks into execution blocks (EB), and sends these blocks to different resources.

2. Basic measures of reliability

Reliability is usually defined as the probability of successful operation of a mission under predefined operating conditions and for a specified mission time. There are many different measures used to measure reliability as presented below.

2.1. Failure Rate and MTTF

The most basic measure of reliability is the failure rate that indicates the average number of failures per unit time as follows:

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{1}{\Delta t} P[System\ Down\ \ in\ (t, t + \Delta t)\ |\ System\ Up\ at\ \ t)] \quad (1)$$

In cases where the failure rate is constant, we have

$$\lambda(t) = \lambda \quad (2)$$

Reliability is found from the failure rate function as follows:

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

For constant failure rate, the reliability is

$$\mathrm{R(t)} = e^{-\int \lambda dt} = e^{-\lambda t} \quad (4)$$

The next measure of reliability is the mean time to failure, or the expectation of the stochastic variable T_U that defines the uptime of the system.

$$MTTF = E[T_U] = \int_0^\infty t f_U(t) dt = \int_0^\infty R(t) dt \quad (5)$$

For a system with exponential probability density function we have:

$$MTTF = E[T_U] = \int_0^\infty t f_U(t) dt = \int_0^\infty e^{-\lambda t} dt = \frac{1}{\lambda} \quad (6)$$

One should not consider MTTF as the normal life time of a system, since the system reliability decreases drastically when that much of the life of the system has elapsed. The reliability at the time equal to MTTF is found to be:

$$R(t = MTTF) = R(\frac{1}{\lambda}) = e^{-\lambda(\frac{1}{\lambda})} = e^{-1} = 0.3678 \quad (7)$$

Table 1 shows typical MTTF values for several components and systems.

TABLE I
MTTF FOR SEVERAL COMPONENTS OR SYSTEMS

Part or system	MTTF (Hours)
Resistor	2500000
Cable	950000
Battery	250000
Electric Motor	100000
Generator	12000
Television	10000-50000
Antenna	20000
Laser	20000
Relay	500000
Magnetron	10000
Radar	600

2.1 Mean Time to Repair (MTTR)

The next important measure affecting a military system's reliability is its maintainability indicated by mean time to repair as follows:

$$MTTR = E[T_D] = \int_0^\infty t f_D(t) dt \quad (8)$$

If the assumption of exponential behavior of the time to repair is made, that is:

$$f_D(t) = \mu e^{-\mu t} \quad (9)$$

then the mean time to repair would be:

$$MTTR = E[T_D] = \int_0^\infty t f_D(t) dt = \int_0^\infty e^{-\mu t} dt = \frac{1}{\mu} \quad (10)$$

Table 2 shows the typical values of MTTR at various maintenance levels.

TABLE 2
TYPICAL VALUES OF MTTR AT THE VARIOUS MAINTENACE LEVELS

Maintenance Level	*MTTR*
Basic	0.5-1 Hours
Intermediate	0.5-3 Hours
Advanced	0.5-4 Hours

The failure rate and MTTR for several products are shown in Table 3.

TABLE 3

THE FAILURE RATE AND MEAN TIME TO REPAIR FOR SEVERAL PRODUCTS ADOPTED FROM DAVIDSON [6]

Product	Failures per year	Mean time to repair (Hours)
Electric heater	0.02	72
Small electric motor	0.03	4
Large electric motors	0.12	148
Pressure vessels	0.001	72
Centrifugal pumps	2.6	24
Oil pumps	0.5	8
High voltage transformers	0.003	24
Steam turbines	0.6	70

2.2 Mean time between failures (MTBF)

Another reliability index used in repairable systems is the mean time between failures as:

$$MTBF = MTTF + MTTR \qquad (11)$$

This index shows the average time between successive failures or repairs. Table 4 indicates typical MTBF values for computers and related equipment.

TABLE 4

MTBF FOR COMMERCIAL COMPUTER EQUIPMENT

Equipment	MTBF (Hours)
Personal Computer	5000-50000
Monochrome Display	20000-30000
Color Display	5000-30000
Hard Drive	30000-90000
Floppy Drive	20000-40000
Tape Drive	7500-12000
Compact Disk Drive	30000-60000
DVD Drive	75000-125000
Keyboard	30000-60000
Dot Matrix Printer	2000-4000
Plotter	30000-40000
Modem	20000-30000
Router	50000-500000
Power Supply	20000-40000

However, military equipments are usually much more sophisticated. Although a lot of effort is exerted to achieve high reliability levels using part derating, redundancy, use of high quality parts and extensive part screening and environmental testing, the mean time between failures for many such military systems is much less than that of commercial or industrial products. Estimated values of the mean time between failures for several military systems are shown in Table 5. A look at the numbers in these tables clarifies the importance of reliability in military systems.

TABLE 5

TYPICAL VALUES OF MTBF FOR SEVERAL MILITARY SYSTEMS

Product	MTBF (Hours)
Ground Fixed Radar	100-200
Tactical Ground Mobile Radar	50-100
Fixed Phase Array Radar	5-10
A Fighter Plane Fire Control Radar	50-200
Airplane Detection Radar	200-2000
Airplane Seek Radar	300-500
Airplane Navigation Radar	300-4500
F-20 Mission Computer	2400
F-14 Fighter Plane	6
F16 APG-66 Radar	150
F16 APG-68 Radar	250
F22 APG-77 Radar	450
Cockpit Honeywell 4x4inch Multifunction Display	7000
MIG-29 Fighter Plane	7.3
Infrared Sensor for B-52	127
ICBM VLF Communications	2738

2.3 Availability

It can be seen from Tables 4 and 5 that the MTBF for military products is much less than that for non-military parts. Another measure of reliability for repairable systems is availability which takes into account both MTTF and MTTR as follows:

$$Availability = \frac{MTBF}{MTBF + MTTR} \qquad (12)$$

Some typical values of MTTF, MTTR and availability for naval military systems are shown in Table 6.

With such low mean time to failure values in military systems, the need to attain high reliability is fulfilled by designing in modularity, and employing techniques to reduce mean time to repair so that the overall availability is high. For example, the expected availability of naval military system should be very high since once a naval vessels goes on a mission, it has no access to ground facilities. This can be seen from the data shown in the table.

3. Factors affecting MTTR

The mean time to repair may be improved by considering the various factors that affect it. This is possible through proper consideration of the operational limitations of military forces deploying the equipment under study. One may cite the following factors:

1- Hours of operation
2- Limitations on equipment's use due to maintenance
3- Mobility requirements of the product
4- The system's need for an operator or lack of such need
5- System's dependability

TABLE 6

MTTF, MTTR AND AVAILABILITY OF SEVERAL NAVAL MILITARY SYSTEMS [7]

System	MTTF (Hours)	MTTR(Hours)	Availability
SWS Submarine Workstation	3500	0.5	0.999857
HLDS Submarine Horizontal Large Screen Display	1500	0.5	0.999666
MicroPUFFS Submarine Sonar	3600	0.5	0.999861
ORION Danish Coastal Radar	3700	0.6	0.999837
SPS-40D Shipboard Radar	252	0.75	0.997032
DRBV Shipboard Radar	2180	0.25	0.999885
MteQ C-band Surface Search Radar	600	0.75	0.998751
W-160 Shipboard FCS	600	0.5	0.999167
AAR-50 Thermal imaging Navigation Set for F/A-18	410	0.3	0.999268
MK 116 Mod7 Fire Control System	875	1	0.998858
AVP Naval Color Dispaly	3000	0.25	0.999916
SPA-25 Raw-Video Radar Repeater	4000	0.33	0.999917
CWS Two-Poisition Command Workstation	3000	0.5	0.999833
AAS-36 Infrared Detecting Set	300	0.5	0.998336
21HS Hull Sonar	1100	1	0.999091

6- System's response time
7- System's operational environment
8- The expertise and level of education of the maintenance personnel for the system
9- The qualifications of the personnel who accompany the system when deployed
10- Testing, fault diagnosis and fault location facilities embedded in the system or accompanying it when dispatched on a mission
11- The hierarchy and design of the various levels of maintenance for the system
12- Use of commonly used components or new designs in the system
13- The degree of maintainability of the system

4. The role of logistics on system availability

The down time of a system should end with the repair of the failed parts and the system should be returned to operational conditions. The downtime may be elongated in military systems due to logistics problems such as inability to provide replacement parts. Therefore, the availability of military systems should be defined as follows:

$$A_O = \frac{MTTF}{MTTF + MDT} \tag{13}$$

The average down time of the system is affected by the mean time to repair as well as the mean time the system is down due to logistics as:

$$MDT = MTTR + MLDT \tag{14}$$

Thus military equipment's availability is:

$$A_o = \frac{MTTF}{MTTF + MTTR + MLDT} \tag{15}$$

2.4 Intrinsic Availability of Military Systems

If we consider ideal logistics conditions and assume

$$MLDT = 0 \tag{16}$$

Then the intrinsic system availability that is the highest possible level of system reliability is:

$$Ao = \frac{MTTF}{MTTF + MTTR} \tag{17}$$

Therefore, the factors that can affect the availability of military products by reducing $MLDT$ and are somewhat controllable by the military forces are as follows:

1- Time to travel for the technical personnel to diagnose and repair the fault
2- Availability of spare parts
3- The time required to obtain the spare part
4- Proper choice of spare parts

5. Redundancy and reliability

It is well known by reliability engineers that system topology affects reliability. For example, in a series system shown in Figure 1 all the parts must function for the system to function. If we assume that we have n parts making up a system each with failure rate λ_i, then the overall failure rate of the system will be

$$\lambda_S = \sum_{i=1}^{n} \lambda_i(t) \tag{18}$$

And the reliability of a series system may be computed from

$$R_S(t) = \prod_{i=1}^{n} R_i(t) \tag{19}$$

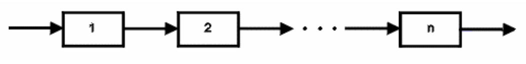

Fig. 1. The reliability block diagram of a simple series system consisting of n components

One of the best approaches to increase the reliability of a military system is the incorporation of redundancy in its topology. This may be in the form of parallel redundancy, r out of n redundancy, or standby redundancy. In a parallel system only one part needs to function for the system to operate as shown in Figure 2.

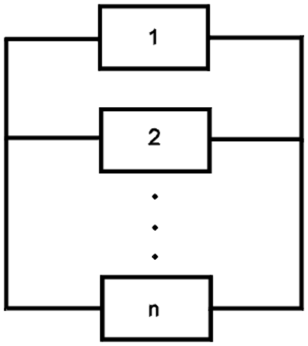

Fig. 2. The reliability block diagram of a fully parallel redundant system consisting of n components

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

$$R_P(t) = 1 - \prod_{i=1}^{n} (1 - R_i(t)) \tag{20}$$

However, in a parallel system in which we enjoy redundancy, the functioning of only one part suffices for the system to operate. In such a system, for example, ten parts employed in parallel each with a reliability of only 0.75 would yield a system with reliability of 0.999999. While having a part with reliability of 0.75 may be normal, obtaining a part with reliability of 0.999999 is either extremely difficult, or improbable if not impossible. This indicates the strength of the use of redundancy to achieve a high level of reliability.

Of course, there are a variety of forms of redundancy in practice. We may have active or standby redundancy. In active redundancy, either a human operator, or some switching elements are used to switch in the redundant device when needed. Although this switching element should have a very high reliability to be effective, this type of redundancy has the benefit of not stressing the standby device when not needed.

The third form of redundancy in design is in voting or r out of n systems in which r components must work for the system to work. This is a topology somewhere in between the series and the parallel configurations both in terms of reliability and cost.

6. Reliability issues in military systems

The reliability of military systems depends on several issues that are not usually considered in industrial or commercial products.

1- Military systems demand high performance specifications usually not required from industrial or commercial products.

2- Designers of military systems usually encounter situations in which they must present the complete system design at once, while designers of other products usually benefit from trial and error and/or perfection of their design through several consecutive brands of a product.

3- Military products are expected to operate under extremely harsh situations which are very difficult to simulate for testing in the laboratory, while commercial or industrial products have well defined operating conditions.

4- Military products should be able to withstand many different environmental stresses such as extreme temperatures, thermal cycling, vibration, mechanical shock, humidity, corrosion, electromagnetic interference, radiation, etc.

5- Some of the maintenance/repair of military systems is done in unsafe conditions and under stress. This poses the personnel to more human errors.

6- Military systems are usually extremely more expensive than industrial or commercial products since there is a need for ruggedness and high reliability.

7- The low sales volume of military parts and goods naturally makes them much more expensive to manufacture.

8- The mission profile for military products including storage, transportation and deployment is usually much more complicated than industrial or commercial products.

9- Naval equipment require higher MTBF since they are deployed in long term naval missions during which there is no access to land-based logistic facilities.

The reliability issues involved in military systems can be easily seen by analyzing what was considered in projects such as the Minuteman ICBM. Initiated around half a century ago and going into an alert-ready status in 1962 as the Minuteman I, the Minuteman III program is the only remaining US Air Force ICBM system today. These underground missiles that are said to be able to deliver nuclear warheads against any target around the globe in less than an hour are supposedly the most threatening weapon of the U.S. Air Force. The Air Force's 500 Minuteman III missiles are located at Malmstrom AFB, Montana holding 200 missiles; Minot AFB, North Dakota holding 150; and F. E. Warren AFB, Wyoming holding another 150 missiles [8]. ICBMs are stored in launch facilities that are unmanned, hardened, and underground structures. A separate missile alert facility serves as the center of assigned security patrol areas. It is the staging point for security forces deployed to the missile complex, and serves as an area away from the main base where maintenance personnel can remain overnight. One missile alert facility controls ten launch facilities making up a flight with five flights making up a squadron. F. E. Warren Air force base has three Minuteman III missile squadrons. Each squadron is responsible for 50 of the ICBMs. Even though this is one of the oldest military systems that still exists, reliability issues are a major concern due to its scope and importance.

Rigorous part control programs were implemented from the very beginning. The computer and memory units were designed with no on/off switches, indicators or electromechanical devices - due to the high failure rate of such devices - except for card and chassis connectors. Strict part screening for especial electrical and environmental screen followed by powered burn in was employed. Extensive and strict use of part derating was implemented in the Minuteman project. All stress factors such as voltage, current, power and temperature were strictly monitored for every part to ensure the part derating policy.

The Minuteman Weapon System Control AN/UYK computer used NDRO plated wire instead of core memory to achieve shorter access time and a lower susceptibility to radiation effects. It had an MTBF of over 25000 hours. The launch control facility system computers that ran continuously for over two decades without a single failure showed no failures. This indicates a case of built-in reliability. The UYK was used in the underground launch control facility and in each silo. The Propulsion Replacement Program (PRP), Guidance Replacement Program (GRP), and Safety Enhanced Reentry Vehicle (SERV) Programs were designed to sustain the Minuteman III ICBM to 2020 and reinforced security measures were put into effect after the 9/11 to extend its life to 2030.

7. Redundancy in military systems

Redundancy is widely used along with other measures in the design of military systems to attain the high levels of reliability desired. Redundancy is used in various ways to increase the reliability of the Minuteman III system. Redundancy is not only used in the hardware design, but it is also implemented in its operation to prevent a nuclear holocaust. For example, it takes more than one man to gain access to the silo or initiate the missile launch. Two men each using both hands must be present to interact with the missile system. The two men have to initiate the procedures within one second of each other. Else, the process will not go through and has to be repeated.

There are various other redundancy measures in effect in both data fusion and decision making systems to increase the reliability. The reliability issues involved in the use of computers in the command and control systems of nuclear weapons were addressed by Borning [9]. The Oct. 5, 1960 warning of a massive missile attack on the United States from the Soviet Union with a certainty of 0.99 was found to be due to spotting of the rising of the moon by BMEWS radars in Thule, Greenland. The June 3, 1980 false alarm in the display system of the Strategic Air Command (SAC) at Offutt Air Force Base indicating that two submarine-launched ballistic missiles were heading towards the United States was pursued by several actions that raised the severity level of the situation. However, this was actually rooted in the failure of a 74175 integrated circuit chip in a Data Digital communications multiplexer computer.

It was the built in redundancy in the system that prevented a nuclear war from happening. The Threat Assessment Conference was convened among the top deputy officers at SAC, NORAD and NMCC as a formal decision making process in the alert state. It was confirmed that there were no indications of an attack on the displays at NORAD, and the indications on the displays at SAC and NMCC did not match each other and were not logical. It was this form of redundancy built into the system – having three systems at SAC, NORAD and NMCC assess the same potential threat – that helped evade a nuclear war.

8. The reliability of missile fuze electronics

The reliability issues discussed are presented in a case study of the electronics of the fuze of surface to air missiles. This is a very important part of any missile and an increased reliability is usually attained by implementing redundancy in design. An example fuze is illustrated in Figure 3. The electronics for this is shown in Figure 4 and is usually attached at the top of the fuze as could be seen from Figure 3.

Fig. 3. A sample missile fuze adopted from Cope [10].

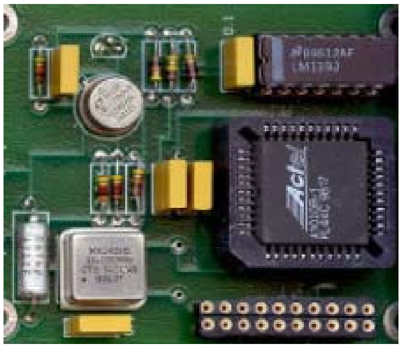

Fig. 4. The electronic board of the sample missile fuze adopted from Cope [10].

One possibility for improved reliability is redundancy in design. The electronic subsystems making up the electronics of a fuze are analyzed in detail as shown in Figure 5. The equations presented above for the reliability of series and parallel systems are used to calculate the failure rate and the mean time to failure for the fuze based on MIL-HDBK-217F [11] and the results are shown in Table 7.

Given the failure rate and mean time to failure for the fuze electronics, we can estimate its reliability based on (4). Another possibility to improve reliability is the integration of parts into more reliable devices. However, this was not an obligation in this research contract.

9. Conclusions

In this paper, the issues involved in the reliability of military systems were reviewed and the various measures of reliability of military systems were reviewed. The various means of improving the reliability of military systems were presented. The importance of redundancy as a means to improve the reliability of military systems was stressed both in hardware and decision making processes in military systems. The failure rate and mean time to failure of an electronic fuze that incorporates redundancy were calculated based on MIL-HDBK-217F.

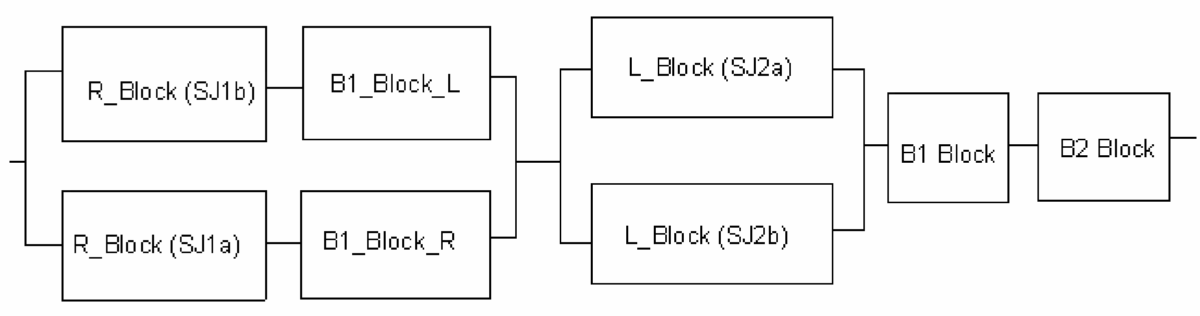

Fig. 5. The reliability block diagram of fuze electronics

Table 7 – Failure rate and mean time to failure calculations for the fuze with redundancy

No.	Module Title	λ_{ML} (FPMH)	λ_{MF} (FPMH)	$MTTF_{ML}$ (HRS)	$MTTF_{MF}$ (HRS)
1	(R_BLOCK(SJ1a)ANDB1_Block_R)OR (R_BLOCK(SJ1b)ANDB1_Block_L)	32.2476	7.2943	31010.05966	137093.3469
2	(L_Block (Sj2a))OR(L_Block(SJ2b))	19.4254	4.3357	51478.99142	23064.2641
3	B1 Block	1.2143	0.2366	823519.7233	422654.688
4	B2 Block	21.9237	9.0469	45612.73873	110535.1004
TOTAL ESTIMATED MTTF:		74.811	20.9135	13367.01822	47816.00402

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