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Reliability Modeling and Growth for a Remotely Piloted Vehicle's Guidance, Navigation and Control Computer System Using Redundancy

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Abstract: Remotely piloted vehicles are usually deployed in various applications especially those requiring remote sensing. RPV's, as they are usually called, are very versatile remote data collection tools, especially for aerial imaging of hard to reach terrain such as mountains and deserts. The sensed images obtained from several such RPV's may be either fused together in a data fusion system, or may be individually used for various engineering applications. The reliability of these unmanned remotely piloted vehicles is of great concern due to the vast amount of expenses incurred in setting up an engineering program to sense RPV obtained data in a given application. The most common approaches for the analysis of the reliability of systems are 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, RBD and state space modeling are used for the analysis of the reliability of the guidance, navigation and control computer system of a remotely piloted vehicle in its various expected operating conditions during its lifetime. It is shown that the reliability of the system may be effectively improved by designing in redundancy where none of the other viable measures of reliability growth 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, RPV, RBD, state space, redundancy

INTRODUCTION

Unmanned vehicles have been of interest for many decades since they can be used in many applications. Simple examples include remotely piloted vehicles for remote sensing applications, unmanned underwater vehicles for performing underwater missions. There are both civilian and military applications for both types of unmanned vehicles. Studies of the reliability of systems date back to the 1940s in both Europe and the United States. The main thrust was behind aerospace applications where severe operating conditions and life-threatening missions were considered. Although these studies were later applied to other areas, they still remain the most important subject in sensitive applications like military, aerospace and life-critical medical electronics.

Remotely piloted vehicles are a member of the larger family of unmanned vehicles. While RPV's are usually controlled from a ground station by a human operator, there are also autonomous unmanned aerial vehicles which fly based on pre-programmed flight patterns using more complex automation systems. They are propelled and powered by a jet or reciprocating engine. Remote sensing functions of such vehicles include electromagnetic spectrum, biological, and chemical sensors. Electromagnetic sensors usually include visual, infrared, or near infrared cameras. Some systems may include radars. The most common form of sensor is a visual camera. Since unmanned vehicles can travel to areas which are dangerous for human pilots, they are very useful instruments for scientific research and engineering remote-sensing applications. Some such systems have been deployed as hurricane hunters.

Warrington (Warrington, Douglas, N., 1978.) presented reliability and maintainability data for the AQUILA RPV-System Technology Demonstrator which he obtained during tests conducted from July to November 1977. He used the data to provide a starting point for reliability growth program for the RPV. The operation of a system that will estimate either the local-relative or absolute-global position of unmanned underwater vehicles

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(UUVs) was described by Goodchild (Goodchild, C., 1993.). The system presented by Goodchild (Warrington, Douglas, N., 1978.) allowed for both autonomous and remote controlled navigation of UUVs. Battipede, et al. (Battipede *et al.,* 2006) presented safety assessment for the demonstrator of the Elettra-Twin-Flyers, an innovative radio-controlled airship for monitoring, telecommunications, advertising and reconnaissance missions in maritime, border and inland environments. They modeled and performed accurate risk analysis on all the subsystems and components of the airship demonstrator.

Integration of discrete parts using modern VLSI gates such as FPAAs and FPGAs are presented as a means of improving system reliability by Peiravi (Peiravi, A., 2008.). The study of the reliability of inertial navigation system reliability (INS) were reported by Rogge (Rogge, Richard, W., 1974.) and the effect of flying hours programs on MTBF were considered showing that time between overhaul (TBO) is the best measurement of INS reliability for the TRC. A reliability analysis was performed on the Navigation and Flight Instruments subsystem of the Boeing Model B-2707 to determine whether the reliability goals can be met or not and to identify the hardware or human factors which are expected to give reliability problems by Lyngaas (Lyngaas and Watson, 1966.). 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 was presented by Boyd *et al.,* (1992). 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.

The improvement in reliability can also be achieved by other means such as accelerated life testing, derating of parts, and use of redundancy in design. The present research 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. To obtain a precise model for the reliability of an RPV, all the various environmental conditions which it experiences as a result of which a portion of its total life may be consumed should be considered. The remotely piloted vehicle experiences many different environments during its lifetime. After its manufacture, and in-house functional testing it may be subjected to accelerated stress testing for screening purposes where a portion of its total life may be consumed. It may also be subjected to operational flight testing. Then upon passing all these quality control tests, it may be stored for a while or delivered to the customer. It experiences ground benign conditions during storage and ground mobile conditions during transportation. Then the customer may perform some inspection, testing and flight testing to make sure it is operational. This is a combination of ground benign and airborne, unmanned environments. Again a portion of its total lifetime will be consumed. Once it is certain that the RPV is perfectly functional, it is subjected to its regular useful lifecycle where it sits for a while - where it experiences ground benign conditions - before being deployed, is deployed in its mission – where it experiences airborne, unmanned conditions, and then taken for maintenance. A precise reliability model for the RPV should consider all the environments the RPV experiences during its lifetime. The Guidance, Navigation and Control Computer System.

The RPV consists of the airframe, engine, servomechanisms and servo actuators, sensors and the guidance, navigation and control computer system. The subject of the reliability modeling and growth program in this study is the autopilot of a remotely piloted vehicle responsible for its proper functioning and monitoring all sensitive devices by receiving their status and issuing proper warning signals to the remote operator in case any problems arise. The initial RPV system was composed of only a single guidance, navigation and control computer system 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 interfaces and the power supply. Still this could 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 guidance, navigation and control computers instead of one was proposed in order to improve the reliability. This section was chosen since it is light and does not drastically affect the RPV's payload. Therefore, the guidance, navigation and control computer in the remotely piloted vehicle was modified 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 computer system is mainly responsible for the generation of the navigation state vector consisting of the position vector, the velocity vector plus yaw, pitch and roll attitude angles. Other viable information such as status, environment, pressure and altitude are also involved. It consists of an electro-optical camera, ultrasonic altitude sensor, compass module, GPS module, RISC processor module, ADC module, control module, telemetry module, and power supply module as depicted in Fig. 3. The detailed electrical schematics are not presented 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 the overall system.

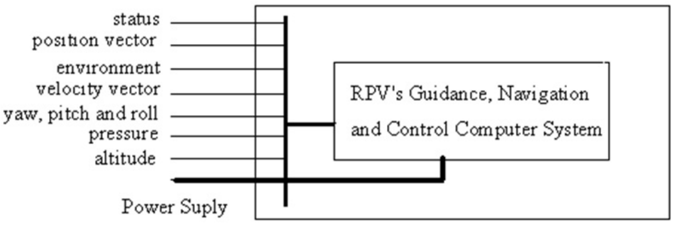

Fig. 1: The initial guidance, navigation and control system of the RPV without redundancy

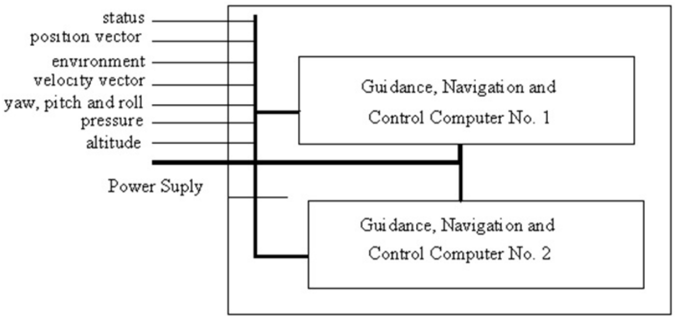

Fig. 2: Guidance, navigation and control system with redundancy

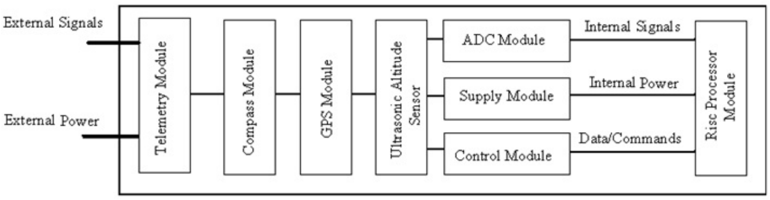

Fig. 3: The interconnections between the various subsystems of the guidance, navigation and control computer

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_{TU} as in (1):

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

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_{TR} as in (2):

$$MTTR = \int_0^\infty t f_{T_R}(t)dt = \frac{1}{\mu} \tag{2}$$

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 in (3):

$$MTBF = E[T_U + T_R] = MTTF + MTTR \tag{3}$$

The failure rate $\lambda(t)$ and the repair rate $\mu(t)$ are each defined as in (4) and (5):

$$\lambda(t) = \underset{\Delta t \to 0}{Lim} \frac{1}{\Delta t} P[System\ Down\ in(t, t+\Delta t) \mid System\ Up\ at\ t)] = \lambda = \frac{1}{MTTF} \tag{4}$$

$$\mu(t) = \underset{\Delta t \to 0}{Lim} \frac{1}{\Delta t} P[System\ Up\ in(t, t+\Delta t) \mid System\ Down\ at\ t)] = \mu = \frac{1}{MTTR} \tag{5}$$

And the reliability of the system may be found from the failure rate function as in (6):

$$\mathrm{R(t)} = e^{-\int \lambda(t).dt} = e^{-\lambda t} \tag{6}$$

The probability of failure is the same as unreliability and may be computed from (7):

$$Q(t) = 1 - R(t) = 1 - e^{-\lambda t} \tag{7}$$

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 in (8):.

$$A = \frac{MTTF}{MTTF + MTTR} = \frac{MTTF}{MTBF} \tag{8}$$

whereas unavailability is given as in (9):

$$\overline{A} = 1 - A = \frac{MTTR}{MTBF} \tag{9}$$

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 general form as in (10):

$$\lambda = \pi_E * f(\pi_T, \pi_Q, \pi_S, \ldots.) \tag{10}$$

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.

Table 1: The various sources for Failure Rate Data

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

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

Table 2: The generic operating conditions per MIL-HDBK-217F

Operating Environment		Notation
1	Ground, Benign	G_B
2	Ground, Fixed	G_F
3	Ground, Mobile	G_M
4	Naval, Sheltered	N_S
5	Naval, Unsheltered	N_U
6	Airborne, Inhabited, Cargo	A_{IC}
7	Airborne, Inhabited, Fighter	A_{IF}
8	Airborne, Uninhabited, Cargo	A_{UC}
9	Airborne, Uninhabited, Fighter	A_{UF}
10	Airborne, Rotary, Winged	A_{RW}
11	Space, Flight	S_F
12	Missile, Flight	M_F
13	Missile, Launch	M_L
14	Cannon، Launch	C_L

Table 3: The various coefficients of operating conditions for various electronic parts per MIL-HDBK-217F

No.	Part Type		Environment													
			GB	GF	GM	NS	NU	AIC	AIF	AUC	AUF	ARW	SF	MF	ML	CL
1	Microcircuits		0.5	2	4	4	6	4	5	5	8	8	0.5	5	12	220
2	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
3	Resistors		1	4	16	12	42	18	23	31	43	63	0.5	37	87	1728
4	Capacitors		1	10	20	7	15	12	15	25	30	40	0.5	20	50	570
5	Inductive Devices		1	6	12	5	16	6	8	7	9	24	0.5	13	34	610
6	Synchros and Resolvers		1	2	12	7	18	4	6	16	25	26	0.5	14	36	680
7	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
8	Switches		1	3	18	8	29	10	18	13	22	46	0.5	25	67	1200
9	Circuit Breakers		1	2	15	8	27	7	9	11	12	46	0.5	25	66	N/A
10	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
11	Interconnection	assemblies (PTH)	1	2	7	5	13	5	8	16	28	19	0.5	10	27	500
12	Connection		1	2	7	4	11	4	6	6	8	16	0.5	9	24	420
13	Meters، Panel		1	4	25	12	35	28	42	58	73	60	1.1	60	N/A	N/A
14	Quartz Crystals		1	3	10	6	16	12	17	22	28	23	0.5	13	32	500
15	Lamps		1	2	3	3	4	4	4	5	6	5	0.7	4	6	27
16	Electronic Filters		1	2	6	4	9	7	9	11	13	11	0.8	7	15	120
17	Fuses		1	2	8	5	11	9	12	15	18	16	0.9	10	21	230

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, and repairability has been studied using the MIL-HDBK-472 (MIL-HDBK-472, 1966) 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 guidance, navigation and control 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 in (11):

$$\lambda_S = \sum_{i=1}^{n} \lambda_i(t) \tag{11}$$

The failure rate of the system may be computed by using a spreadsheet such as shown in Table 4 for the guidance, navigation and control system with redundancy. Then the reliability may be computed as in (12):

$$R_S(t) = \prod_{i=1}^{n} R_i(t) \tag{12}$$

Fig. 4: The reliability block diagram (RBD) of each guidance, navigation and control computer

The various failure rate data were obtained from data sources such as MIL-HDBK-217F (MIL-HDBK-217F, 1995.) or EPRD (William Denson, 1997).
The equivalent part for n_r redundant parts in parallel is computed as in (13):

$$R_P(t) = 1 - \prod_{i=1}^{n} (1 - R_i(t)) \tag{13}$$

The State Space Model of the System:

The inclusion of a redundant computer in the guidance, navigation and control system improves the reliability of the system. The state space model of the guidance, navigation and control 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).

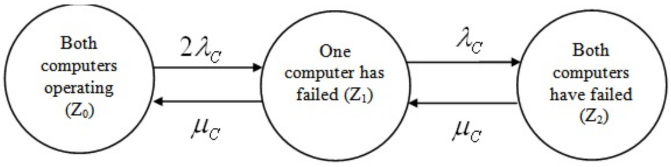

Fig. 5(a): The state space diagram of the proposed system assuming repair after both fail

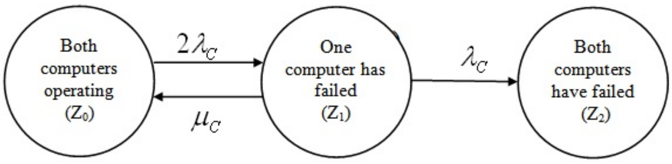

Fig. 5(b): The state space diagram of the proposed system assuming no repair after both fail

The state space model can be solved using the following equations as in (14):

$$\begin{aligned} &\dot{p}(t) = p(t)A \\ &\sum_{i=1}^{3} p_i(t) = 1.0 \end{aligned} \tag{14}$$

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 of Fig 5a or Fig 5b. 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 in (15):

$$MTTF_S = \frac{1}{\lambda_S} = \frac{(3\lambda_C + \mu_C)}{3\lambda_C^{2}} \tag{15}$$

The system availability is as in (16):

$$A_S = \frac{\mu_C(\mu_C + 2\lambda_C)}{\mu_C^{2} + 2\lambda_C(\mu_C + \lambda_C)} \tag{16}$$

And the system reliability is as in (17):

$$R_S(t) = e^{-\frac{3\lambda_c^2}{(3\lambda_c+\mu_c)}t} \tag{17}$$

The system reliability is computed for four different operating conditions of Ground Benign G_B; Ground Mobile G_M; Airborne, Inhabited, Cargo, $A_{IC;}$ and Airborne, Uninhabited, Cargo, A_{UC}. The overall estimated failure rates for the various subsystems of the guidance, navigation and control computer in Failures per Million Hours are shown in Table 4. As can be seen from Table 4 it can be seen that the failure rates are much higher in more severe operating conditions. Table 5 shows the Failure Rate and MTTF for one guidance, navigation and control computer while Table 6 shows the reliability measures for the guidance, navigation and control computer system considering various operating environments using redundancy. The mean time to repair MTTR for the guidance, navigation and control computer is estimated to be $MTTR_C = \frac{1}{\mu_C} = 1.49$ Hours per MIL-HDBK-472 (MIL-HDBK-472, 1966) considering the necessary steps to perform the disassembly/assembly.

The results presented in the above two Tables may be used to make a comparison of the system unavailability with and without redundancy in the various expected operating conditions. Fig. 6 shows a considerable improvement in unavailability measure in all various expected environmental conditions.

Moreover, the reliability of the guidance, navigation and control computer during the expected useful lifetime of the system can be computed using the mean time to failure shown in the above Tables. For example, the reliability under A_{UC} operating conditions for using just a single computer is as in (18):

Table 4: The overall estimated failure rates for the various subsystems of the guidance, navigation and control computer in Failures Per Million Hours without using redundancy

No.	Subsystem	Operating Conditions			
		G_B	G_M	A_{IC}	A_{UC}
1	Risc Processor Module	9.858	81.779	76.054	121.461
2	Telemetry Module	3.162	33.631	27.233	54.154
3	Analog to Digital Converter Module	5.714	59.152	58.886	101.607
4	Power Supply Module	9.728	111.877	126.481	218.336
5	GPS Module	1.287	23.468	19.626	47.623
6	Compass Module	4.16	47.933	54.623	87.771
7	Ultrasonic Altitude Sensor	13.142	118.304	137.204	217.517
8	Control Module	11.568	127.062	121.944	186.595

Table 5: Reliability measures - the Failure Rate, MTTF, MTTR and unavailability for one guidance, navigation and control computer

Reliability Measure	Operating Conditions			
	G_B	G_M	A_{IC}	A_{UC}
Failure Rate (Failure/10^6 Hours)	48.619	603.206	622.051	1034.527
MTTF (Hours)	20568.09	1657.81	1607.58	968.48
MTTR (Hours)	1.49	1.49	1.49	1.49
MTBF(Hours)	20569.58	1659.3	1609.07	967.97
$\bar{A}_c$ (Percent)	0.00724	0.08979	0.092600	0.15393

Table 6: Reliability measures - the Failure Rate, MTTF, MTTR and unavailability for the guidance, navigation and computer system considering various operating environments using redundancy

Reliability Measure	Operating Conditions			
	G_B	G_M	A_{IC}	A_{UC}
Failure Rate (Failure/10^6 Hours)	24.309	301.603	311.025	517.263
MTTF (Hours)	41137.02	3315.61	3215.17	1933.25
MTTR (Hours)	1.49	1.49	1.49	1.49
MTBF(Hours)	41138.51	3317.1	3216.66	1934.74
$\bar{A}_c$ (Percent)	0.00362	0.04491	0.04632	0.07701

$$R_c(t) = 1 - Q_c(t) = Exp(-0.001034527t) \tag{18}$$

while the reliability under the same operating conditions for using redundancy as proposed is as in (19):

$$R_c(t) = 1 - Q_c(t) = Exp(-0.000517263t) \tag{19}$$

The reliability of the guidance, navigation and control computer during the time it is being transported before flight may be found using the mean time to failure shown in the above Tables. For example, the reliability under A_{GM} operating conditions for using just a single computer is as in (20):

$$R_c(t) = 1 - Q_c(t) = Exp(-0.000603206t) \tag{20}$$

while the reliability under the same operating conditions for using redundancy as proposed is as in (21):

$$R_c(t) = 1 - Q_c(t) = Exp(-0.000301603t) \tag{21}$$

The failure rates computed above may be used to obtain the reliability of the system for any operational scenario. For example, if we assume that the system with redundancy is kept in storage for 24 hours, then transported to its flight location in 2 hours and deployed for 10 hours, we can calculate the reliability as given in (22),(23) and (24) and shown in Fig.7 in comparison with the reliability of the same system without using redundancy under the same set of assumed operational conditions.

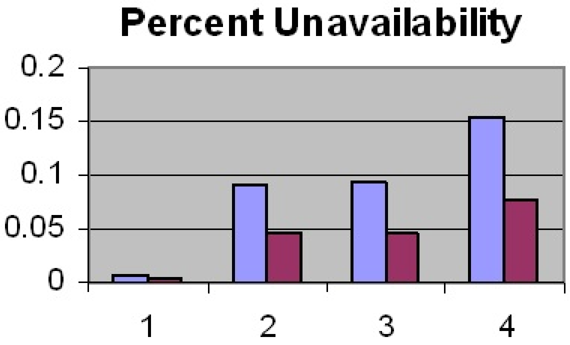

Fig. 6: A comparison of percent unavailability of the system with and without redundancy in various operating conditions(1 indicates GB conditions; 2 indicates GM conditions; 3 indicates IC conditions and 4 indicates UC conditions).

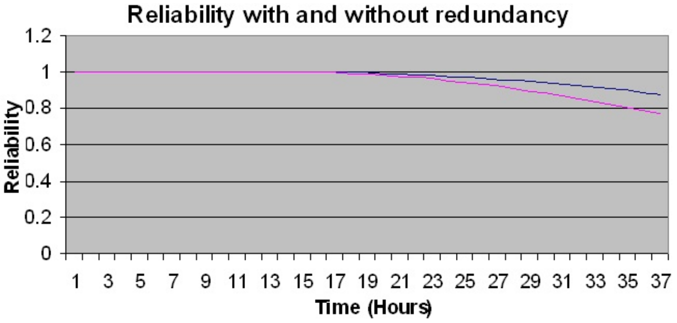

Fig. 7: A comparison of reliability of the system with and without redundancy versus time for an assumed three day operational scenario showing the reliability improvement by using redundancy.

$$R_c(t) = Exp(-0.000024309t) \text{ r t=0 to 24 Hrs} \tag{22}$$

$$R_c(t) = (Exp(-0.000024309*24))Exp(-0.000301603(t-24)) \text{ for t=24 to 26Hrs} \tag{23}$$

$$R_c(t) = (Exp(-0.000024309*24))(Exp(-0.000301603*2))Exp(-0.000517263(t-26)) \text{ for t=26 to 36Hrs} \tag{24}$$

Conclusions:

The consideration of expected operating conditions are very important in the analysis of the reliability of guidance, navigation and control of remotely piloted vehicles since they experience various different conditions during their lifetime. 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 such sophisticated equipment where not much else can be done to improve system reliability. A substantial decrease in MTTF and unavailability, and a substantial improvement in reliability were achieved using the proposed scheme.

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