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Cost-Benefit Analysis of a Two Similar Cold Standby System with International Space Station Failure Caused by Computer Failure and Failure of Main Bus Switching Unit #1 and Replacement EVA

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Abstract—*Since construction started, the International Space Station (ISS) programme has had to deal with several maintenance issues, unexpected problems and failures. These incidents have affected the assembly timeline, led to periods of reduced capabilities of the station and in some cases could have forced the crew to abandon the space station for safety reasons, had these problems not been resolved.*

We have taken units-International Space Station (ISS) failure caused due to computer failure and due to Failure of Main Bus Switching Unit #1 and Replacement EVA with failure time distribution as exponential and repair time distribution as General. We have find out MTSF, Availability analysis, the expected busy period of the server for repair when the failure of ISS caused due to computer failure in (0, t], expected busy period of the server for repair in (0,t], the expected busy period of the server for repair when failure of ISS caused due to Failure of Main Bus Switching Unit #1 and Replacement EVA in (0,t], the expected number of visits by the repairman for failure of ISS units due to computer failure in (0,t], the expected number of visits by the repairman for failure of ISS caused due to Failure of Main Bus Switching Unit #1 and Replacement EVA in (0,t] and Cost-Benefit analysis using regenerative point technique. A special case using failure and repair distributions as exponential is derived and graphs have been drawn.

Keyword: *Cold Standby, International Space Station (ISS) failure caused due to computer failure and due to Failure of Main Bus Switching Unit #1 and Replacement EVA, MTSF, Availability, Busy period, Cost-Benefit Analysis*

1. INTRODUCTION

2007–Computer failure On 14 June 2007, during Expedition 15 and flight day 7 of STS-117's visit to ISS, a computer malfunction on the Russian segments at 06:30 UTC left the station without thrusters, oxygen generation, carbon dioxide scrubber, and other environmental control systems, causing the temperature on the station to rise. A successful restart of the computers resulted in a false fire alarm that woke the crew at 11:43 UTC.

By 15 June, the primary Russian computers were back online, and communicating with the US side of the station by bypassing a circuit, but secondary systems remained offline. NASA reported that without the computer that controls the oxygen levels, the station had 56 days of oxygen available.

By the afternoon of 16 June, ISS Program Manager Michael Suffredini confirmed that all six computers governing command and navigation systems for Russian segments of the station, including two thought to have failed, were back online and would be tested over several days. The cooling system was the first system brought back online. Troubleshooting of the failure by the ISS crew found that the root cause was condensation inside the electrical connectors, which led to a short-circuit that triggered the power off command to all three of the redundant processing units. This was initially a concern because the European Space Agency uses the same computer systems, supplied by EADS Astrium Space Transportation, for the *Columbus* laboratory module and the Automated Transfer Vehicle. Once the cause of the malfunction was understood, plans were implemented to avoid the problem in the future.

2. 2011-2012–FAILURE OF MAIN BUS SWITCHING UNIT #1 AND REPLACEMENT EVA

The four Main Bus Switching Units (MBSUs, located in the S0 truss), control the routing of power from the four solar array wings to the rest of the ISS. In late 2011 MBSU-1, while still routing power correctly, ceased responding to commands or sending data confirming its health, and was scheduled to be swapped out at the next available EVA. In each MBSU, two power channels feed 160V DC from the arrays to two DC-to-DC power converters (DDCUs) that supply the 124V power used in the station. A spare MBSU was already on board, but the Aug 30 2012 EVA failed to be completed when a bolt being tightened to finish installation of the spare unit jammed before electrical connection was secured. The loss of MBSU-1 limited the station to 75% of its normal power capacity, requiring minor limitations of normal operations until the issue was addressed.

A second EVA to tighten the balky bolt, to complete the installation of the replacement MBSU-1 in an attempt to restore full power, was scheduled for Wednesday, 5 September. Yet in the meantime, a third solar array wing went offline due to some fault in that array's Direct Current Switching Unit (DCSU) or its associated system, further reducing ISS power to just five of the eight solar array wings for the first time in several years.

On 5 September 2012, in a second, 6 hr, EVA to replace MBSU-1, astronauts Suni Williams and Aki Hosihde successfully restored the ISS to 100% power.

In this paper, we have taken failure of ISS caused due to computer failure and due to failure of Main Bus Switching Unit #1 and Replacement EVA which are non-instantaneous in nature. Here, we investigate a two identical cold standby –a system in which offline unit cannot fail. When there is failure of Main Bus Switching Unit #1 and Replacement EVA within specified limit, it operates as normal as before but if these are beyond the specified limit the operation of the unit is stopped to avoid excessive damage of the unit and as when there is failure of Main Bus Switching Unit #1 and Replacement EVA continues going on some characteristics of the unit change which we call failure of the unit. After failure of ISS caused due to failure of Main Bus Switching Unit #1 and Replacement EVA the failed unit undergoes repair immediately according to first come first served discipline.

3. ASSUMPTIONS

1. The system consists of two similar cold standby units. The failure time distributions of the operation of the unit stopped automatically, the computer failure and Failure of Main Bus Switching Unit #1 and Replacement EVA are exponential with rates λ_1, λ_2 and λ_3 whereas the repairing rates for repairing the failed system due to computer failure and due to Failure of Main Bus Switching Unit #1 and Replacement EVA are arbitrary with CDF G_1 (t) & G_2 (t) respectively.
2. When there is failure of Main Bus Switching Unit #1 and Replacement EVA within specified limit, it operates as normal as before but if these are beyond the specified limit the operation of the unit is avoided and as the failure of Main Bus Switching Unit #1 and Replacement EVA continues goes on some characteristics of the unit change which we call failure of the unit.
3. The failure of Main Bus Switching Unit #1 and Replacement EVA actually failed the units. The failure of Main Bus Switching Unit #1 and Replacement EVA is non-instantaneous and it cannot occur simultaneously in both the units.
4. The repair facility works on the first fail first repaired (FCFS) basis.
5. The switches are perfect and instantaneous.
6. All random variables are mutually independent.

4. SYMBOLS FOR STATES OF THE SYSTEM

Superscripts O, CS, SO, CF, MBSUF -Operative, cold Standby, Stops the operation, ISS failure caused due to computer failure, due to Failure of Main Bus Switching Unit #1 and Replacement EVA respectively

Subscripts nmbsu, umbsu, cf, ur, wr, uR -No failure of Main Bus Switching Unit #1 and Replacement EVA, under failure of Main Bus Switching Unit #1 and Replacement EVA, computer failure, under repair, waiting for repair, under repair continued respectively

Up states–0, 1,3 ; Down states–2,4,5,6,7

5. STATES OF THE SYSTEM

0(O_{nmbsu}, CS_{nmbsu}) One unit is operative and the other unit is cold standby and there is no failure of Main Bus Switching Unit #1 and Replacement EVA in both the units.

1(SO_{umbsu}, O_{nmbsu}) The operation of the first unit stops automatically due to failure of Main Bus Switching Unit #1 and Replacement EVA and cold standby unit starts operating with no failure of Main Bus Switching Unit #1 and Replacement EVA.

2(SO_{umbsu}, $MBSUF_{mbsu,,ur}$) The operation of the first unit stops automatically due to failure of Main Bus Switching Unit #1 and Replacement EVA and the other unit fails due to failure of Main Bus Switching Unit #1 and Replacement EVA undergoes repair.

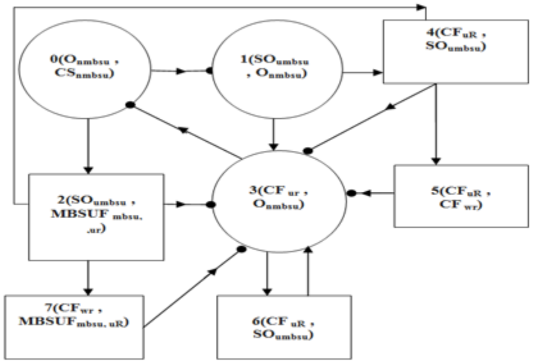

Fig. 1: The State Transition Diagram ● regeneration point
○ Up State ☐ down state

3(CF_{ur}, O_{nmbsu}) The first unit fails due to computer failure undergoes repair and the other unit continues to be operative with no Torn solar panel failure.

4(CF_{uR}, SO_{umbsu}) The one unit fails due to computer failure continues to be under repair and the other unit also stops automatically due to failure of Main Bus Switching Unit #1 and Replacement EVA.

5(CF_{uR}, CF_{wr}) The repair of the first unit is continued from state 4 and the other unit failed due to computer failure is waiting for repair.

6(CF_{uR}, SO_{umbsu}) The repair of the first unit is continued from state 3 fails due to computer failure and operation of other unit stops automatically due to failure of Main Bus Switching Unit #1 and Replacement EVA.

7(CF_{wr}, $MBSUF_{mbsu,\ uR}$) The repair of failed unit due to failure of Main Bus Switching Unit #1 and Replacement EVA is continued from state 2 and the first unit failed due to computer failure is waiting for repair.

Transition Probabilities

Simple probabilistic considerations yield the following expressions :

$p_{01} = \frac{\lambda 1}{\lambda 1+\lambda 3}$, $p_{02} = \frac{\lambda 3}{\lambda 1+\lambda 3}$, $p_{13} = \frac{\lambda 2}{\lambda 1+\lambda 2}$, $p_{14} = \frac{\lambda 1}{\lambda 1+\lambda 2}$

$p_{23} = \lambda_1 G_2^*(\lambda_2)$, $p_{23}^{(7)} = \lambda_2 G_2^*(\lambda_2)$, $p_{24} = \overline{G}_2^*(\lambda_2)$, $p_{30} = G_1^*(\lambda_1)$, $p_{33}^{(6)} = \overline{G}_1^*(\lambda_1)$

$p_{43} = G_1^*(\lambda_2)$, $p_{43}^{(5)} = G_1^*(\lambda_2)$ (1)

we can easily verify that

$p_{01} + p_{02} = 1$, $p_{13} + p_{14} = 1$, $p_{23} + p_{23}^{(7)} + p_{24} = 1$, $p_{30} + p_{33}^{(6)} = 1$, $p_{43} + P_{43}^{(5)} = 1$ (2)

and mean sojourn time is

$\mu_0 = E(T) = \int_0^\infty P[T > t]dt = -1/\lambda_1$

Similarly

$\mu_1 = 1/\lambda_2$, $\mu_2 = \int_0^\infty e^{-}\lambda 1\overline{G}1(t)dt$, $\mu_4 = \int_0^\infty e^{-}\lambda 2\overline{G}1(t)dt$ (3)

Mean Time To System Failure

We can regard the failed state as absorbing

$\theta_0(t) = Q_{01}(t)[s]\theta_1(t) + Q_{02}(t)$, $\theta_1(t) = Q_{13}(t)[s]\theta_3(t) + Q_{14}(t)$ $\theta_3(t) = Q_{30}(t)[s]\theta_0(t) + Q_{33}^{(6)}(t)$ (4-6)

Taking Laplace-Stieltjes transforms of eq. (4-6) and solving,we get

$Q_0^*(s) = N_1(s) / D_1(s)$ (7)

where

$N_1(s) = Q_{01}^*(s)\ \{\ Q_{13}^*(s)\, Q_{33}^{(6)*}(s) + Q_{14}^*(s)\} + Q_{02}^*(s)$

$D_1(s) = 1 - Q_{01}^*(s)\quad Q_{13}^*(s)\, Q_{30}^*(s)$

Making use of relations (1) & (2) it can be shown that $Q_0^*(0)$ =1, which implies

that $\theta_1(t)$ is a proper distribution.

$$\text{MTSF} = E[T] = \frac{d}{ds}\theta_0(s) = (D_1'(0) - N_1'(0)) / D_1(0) \Big|_{s=0}$$

$= (\mu_0 + p_{01}\mu_1 + p_{01}p_{13}\mu_3) / (1 - p_{01}p_{13}p_{30})$ (8)

where

$\mu_0 = \mu_{01} + \mu_{02}$, $\mu_1 = \mu_{13} + \mu_{14}$, $\mu_2 = \mu_{23} + \mu_{23}^{(1)} + \mu_{24}$,
$\mu_3 = \mu_{30} + \mu_{33}^{(6)}$
$\mu_4 = \mu_{43} + \mu_{43}^{(5)}$

Availability analysis

Let $M_i(t)$ be the probability of the system having started from state i is up at time t without making any other regenerative state . By probabilistic arguments, we have

The value of $M_0(t) = e^{-}\lambda_1 t\, e^{-}\lambda_3\ t$, $M_1(t) = e^{-}\lambda_1 t\, e^{-}\lambda_2\ t$, $M_3(t) = e^{-}\lambda_1\overline{G}_1(t)$. (9)

The point wise availability $A_i(t)$ have the following recursive relations

$A_0(t) = M_0(t) + q_{01}(t)[c]A_1(t) + q_{02}(t)[c]A_2(t)$,
$A_1(t) = M_1(t) + q_{13}(t)[c]A_3(t) + q_{14}(t)[c]A_4(t)$,
$A_2(t) = \{q_{23}(t) + q_{23}^{(7)}(t)\}[c]A_3(t) + q_{33}^{(6)}(t)[c]A_3(t)$
$A_3(t) = M_3(t) + \{q_{30}(t) + q_{33}^{(6)}(t)\}[c]A_3(t)$, $A_4(t) = \{q_{43}(t) + q_{43}^{(5)}(t)[c]A_3(t)$

(10 -14)

Taking Laplace Transform of eq. (10-14) and solving for $\hat{A}_0(s)$

$\hat{A}_0(s) = N_2(s) / D_2(s)$ (15)

Where0

$N_2(s) = (1 - \hat{q}_{33}^{(6)}(s))\ \widehat{M}_0(s) + [\ \hat{q}_{01}(s)\{\widehat{M}_1(s) + (\hat{q}_{13}(s) + \hat{q}_{14}(s)\ (\hat{q}_{43}(s) + \hat{q}_{43}^{(5)}(s)))\} + \hat{q}_{02}(s)\{\hat{q}_{23}(s)) + \hat{q}_{23}^{(1)}(s)) + \hat{q}_{24}(s)(\hat{q}_{43}(s) + \hat{q}_{43}^{(5)}(s))\}]\ \widehat{M}_3(s)$

$D_2(s) = (1 - \hat{q}_{33}^{(6)}(s)) - \hat{q}_{30}(s)\ [\hat{q}_{01}(s)\{\ \hat{q}_{13}(s) + \hat{q}_{14}(s)\ (\hat{q}_{43}(s) + \hat{q}_{43}^{(5)}(s))\}$
$+ \hat{q}_{20}(s)\{\hat{q}_{23}(s) + \hat{q}_{23}^{(7)}(s) + \hat{q}_{24}(s)(\hat{q}_{43}(s)) + \hat{q}_{43}^{(5)}(s))\}]$

The steady state availability

$A_0 = \lim_{t\to\infty}[A_0(t)] = \lim_{s\to 0}[s\,\hat{A}_0(s)] = \lim_{s\to 0}\frac{s\,N_2(s)}{D_2(s)}$

Using L' Hospitals rule, we get

$A_0 = \lim_{s\to 0}\frac{N_2(s) + s\ N_2'(s)}{D_2'(s)} = \frac{N_2(0)}{D_2'(0)}$ (16)

where

$N_2(0) = p_{30}\widehat{M}_0(0) + p_{01}\widehat{M}_1(0)\ \widehat{M}_3(0))$

$D_2'(0) = \mu_3 + [\mu_0 + p_{01}(\mu_1 + p_{14}\mu_4 + p_{02}(\mu_2 + p_{24}\mu_4)]\ p_{30}$

The expected up time of the system in (0,t] is

$\lambda_u(t) = \int_0^\infty A_0(z)dz$ So that $\widehat{\lambda_u}(s) = \frac{\hat{A}_0(s)}{s} = \frac{N_2(S)}{SD_2(S)}$ (17)

The expected down time of the system in (0,t] is

$\lambda_d(t) = t - \lambda_u(t)$ So that $\widehat{\lambda_d}(s) = \frac{1}{s^2} - \widehat{\lambda_u}(s)$ (18)

Similarly, we can find

1. The expected busy period of the server when the operation of the unit stops automatically when there is

Failure of Main Bus Switching Unit #1 and Replacement EVA in (0,t]-R_0

2. The expected Busy period of the server for repair when there is computer failure in (0,t] -B_0
3. The expected busy period of the server when there is Failure of Main Bus Switching Unit #1 and Replacement EVA in (0,t] - P_0
4. The expected number of visits by the repairman for repairing when there is Failure of Main Bus Switching Unit #1 and Replacement EVA in (0,t] - H_0
5. The expected number of visits by the repairman for repairing the units when there is computer failure in (0,t] - V_0

Cost Benefit Analysis

The cost-benefit function of the system considering mean up-time, expected busy period of the system under Failure of Main Bus Switching Unit #1 and Replacement EVA when the units stops automatically, expected busy period of the server for repair when there is computer failure, expected total repair cost for repairing the units when there is failure of Main Bus Switching Unit #1 and Replacement EVA, expected number of visits by the repairman for failure of Main Bus Switching Unit #1 and Replacement EVA, expected number of visits by the repairman when there is computer failure.

The expected total cost-benefit incurred in (0,t] is
C(t) = Expected total revenue in (0,t]
-expected busy period of the system under failure of Main Bus Switching Unit #1 and Replacement EVA when the units automatically stop in (0,t]
-expected total repair cost when there is computer failure in (0,t]
-expected total repair cost for repairing the units when there is failure of Main Bus Switching Unit #1 and Replacement EVA in (0,t]
- expected number of visits by the repairman for repairing the units when there is failure of Main Bus Switching Unit #1 and Replacement EVA in (0,t]
- expected number of visits by the repairman for repairing when there is computer failure in (0,t]
The expected total cost per unit time in steady state is

$$C = \lim_{t\to\infty}(C(t)/t) = \lim_{s\to 0}(s^2 C(s))$$
$$= K_1A_0 - K_2 R_0 - K_3B_0 - K_4 P_0 - K_5 H_0 - K_6 V_0$$

where
K_1 - revenue per unit up-time,
K_2 -cost per unit time for which the system is under failure of Main Bus Switching Unit #1 and Replacement EVA when units automatically stop.
K_3 - cost per unit time for which the system is under unit repair when there is computer failure
K_4 - cost per unit time for which the system failure due to failure of Main Bus Switching Unit #1 and Replacement EVA

K_5 - cost per visit by the repairman when there is computer failure,
K_6 - cost per visit by the repairman when there is failure of Main Bus Switching Unit #1 and Replacement EVA.

6. CONCLUSION

After studying the system, we have analyzed graphically that when the **failure rate** due to operation of the unit stops automatically, due to computer failure and due to failure of Main Bus Switching Unit #1 and Replacement EVA increases, the MTSF and steady state availability decreases and the cost function decreased as the failure increases.

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