A Preliminary Deep Space Station Operational Availability Model

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A method is given for determining deep space station operational availability as a function of the reliability of replaceable subassemblies and the time required to replace them when they fail. It is shown that a reduction in replacement time can have a significant effect on station operational availability.

I. Introduction

In this paper DSS operational availability is analytically defined in terms of subassembly failure rates and replacement rates. In Ref. 1 we assumed that down time occurred only when a spare was not available to replace a failed piece of equipment. Replacement time was assumed to be negligible. However, since replacement time is very often not negligible, its effect on system down time is analyzed. Thus, down time for a piece of equipment is defined to occur only from time delays due to fault detection, fault isolation, disassembly, removal and replacement of the faulty unit, reassembly, checkout, and alignment if required. It is shown that a reduction in these time delays may significantly increase DSS operational availability.

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II. General Assumptions

We assume that a signal data path for any DSS function (system) can be characterized by s unique subassemblies which are functionally required for station operations. Failure of the system occurs when any one of the required subassemblies fails. Any subassembly may be configured as a single module or as a standby or parallel configuration having several identical modules. All failed modules can be removed and replaced by operational off-line spares, and then repaired. We further assume that the optimal number of offline operational spares has been determined in accordance with Ref. 2, and the frequency of running out of spares is negligible.

III. Determination of DSS Operational Availability

The up-time ratio (UTR) for a system or subassembly is defined as the fraction of the time that the system or subassembly is operational, i.e. "up." This ratio turns out (Ref. 3) to be given by

$$UTR = \frac{1}{1 + \frac{MDT}{MTBF}}$$

where MTBF is the mean time between failures and MDT is the mean down time before operation is restored. Applying this formula to the DSS as a whole, we can see that system reliability is only one factor in assuring high operational availability. Short downtimes are equally important. Figure 1 shows how station operational availability (UTR) increases as the MDT is decreased.

Actual computation of MDTs and MTBFs for an entire station is not feasible. Instead, station UTR can be calculated by analyzing directly the failure rates and replacement rates of subassemblies. For operation along a signal data path, assume that s subassembly functions must be performed, indexed by $i = 1, \cdots, s$. Then the UTR for that data path is given by

$$\text{UTR} = \prod_{i=1}^{s} \text{UTR}_i$$

where UTR_i is the up-time ratio for the ith subassembly. This formula is based on the assumed independence of failures of distinct subassemblies.

To calculate the UTR_i's, we assume that for a given subassembly function there are $n + N$ identical modules which perform the given function. Of these, only n are operating at any time (and even fewer may be required to perform the required function). The other N are on-line spares ($N = 0$ is allowed). While operating, each of the n modules is subject to a constant failure rate, λ. Once failed, it takes a time T, which is assumed exponentially distributed, to restore the module to an operating condition. T includes the time required to detect and isolate the fault, disassemble and verify, remove and replace with an off-line spare component, etc., until the subassembly is finally checked out and restored to operation or to the on-line spare status. The switching time to an on-line spare is assumed to be negligible. The restoration rate, μ, is defined as the reciprocal of the mean value of T.

These assumptions lead to the model of a Birth and Death process. The state variable, j, is the number of modules down among the total $n + N$. The possible values of j are 0, 1, 2, $\cdots$ up to the point (if any) where shutdown is prescribed. In any case, $j \leq N$ means that all n operating modules are operable, while $j = N + 1, \cdots$ means that fewer than n modules are operable. Over a long period of time, the fraction of the time spent in states $j = 0, 1, 2, \cdots$ is given by the so-called stationary probabilities, $P_0, P_1, \cdots$. These can be calculated by the following scheme.

Define

$$\lambda_j = \begin{cases} n\lambda \text{ for } j \leq N \\ (N+n-j)\lambda \text{ for } j > N \end{cases}, \qquad j \geq 0$$

$$\mu_j = \mu \cdot \text{minimum}\,(j, r), \qquad j \geq 1$$

where

r = number of module replacements that can be worked on simultaneously

$$q_0 = 1$$

$$q_1 = \lambda_0$$

$$q_{j+1} = \mu_{j+1}^{-1}[q_j\,(\lambda_j + \mu_j) - q_{j-1}\lambda_{j-1}], \qquad j \geq 1 \quad .$$

Then

$$P_j = \frac{q_j}{\sum_i q_i}, \qquad j \geq 0.$$

Now, suppose m of the operating modules are required to perform the intended function ($1 \leq m \leq n$). Then

$$UTR_i = \sum_{j=0}^{n+N-m} P_j$$

After determining the values of UTR_i separately for each subassembly $i = 1, \cdots, s$, we multiply these values together to obtain the UTR for the entire signal data path. Where there are redundant data paths in the DSS, their UTRs are easily used to compute an overall UTR for the station.

As an example of these considerations, consider the signal data path with five subassembly functions as diagrammed in Fig. 2. The first three functions are performed by individual modules with no redundancy. The fourth function is performed by a module with N on-line spares. The fifth function is performed by an (m, n) parallel configuration of modules. Here there are $N = 0$ on-line spares, but only m of the n modules are required to operate.

Letting $P_j^{(k)}$ denote the probabilities of states, j, for subassemblies $k = 1, 2, 3, 4, 5$, we have

$$UTR_1 = P_0^{(1)}, \quad UTR_2 = P_0^{(2)}, \quad UTR_3 = P_0^{(3)}$$

since the first three subassemblies are up only when $j = 0$. For the fourth subassembly we have

$$UTR_4 = \sum_{j=0}^{N} P_j^{(4)}$$

since only the N on-line spares could be down without causing the subassembly function to fail. For the fifth subassembly, which is in the (m, n) configuration, we have

$$UTR_5 = \sum_{j=0}^{n-m} P_j^{(5)}$$

Thus, overall

$$UTR = P_0^{(1)} \cdot P_0^{(2)} \cdot P_0^{(3)} \cdot \sum_{j=0}^{N} P_j^{(4)} \cdot \sum_{j=0}^{n-m} P_j^{(5)}$$

IV. Conclusions

The present model expresses DSS operational availability as a computable function of the failure rates and restoration rates of subassemblies. In so doing, it permits a quantitative analysis of the effect upon station availability of many factors. Among these factors are component reliability, subassembly redundancy design, DSS operating configuration, fault detection and diagnosis, the type of spares provided, and crew size and skill levels. These and other factors affect the parameters of the Birth and Death process model from which the uptime ratios are computed.

In particular, the model provides a suitable framework for analyzing the DSS availability resulting from the various automation schemes currently under study. It is anticipated that this analysis can be used to equate system availability levels for different schemes, thereby permitting a meaningful comparison of extended life-cycle costs.

References

1. Eisenberger, I., et al., "A Preliminary Study of Spares Provisioning for the Deep Space Network," in *The Deep Space Network*, Technical Report 32-1526, Vol. XVIII, pp. 102–110, Jet Propulsion Laboratory, Pasadena, Calif., Dec. 15, 1973.
2. Eisenberger, I., et al., "Cost Effective Spares Provisioning for the Deep Space Network," in *The Deep Space Network*, Progress Report 42-20, pp. 128–135, Jet Propulsion Laboratory, Pasadena, Calif., April 15, 1974.
3. Rau, J. G., *Optimization and Probability in Systems Engineering*, Van Nostrand Reinhold Company, New York, 1970.

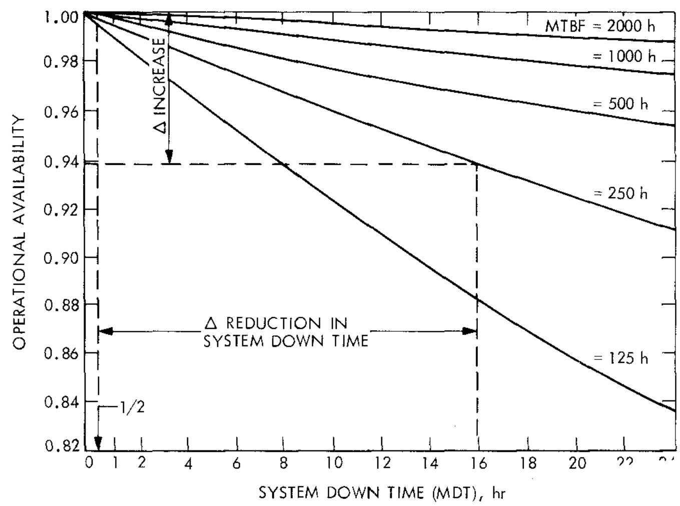

Fig. 1. DSS operational availability versus system mean down time

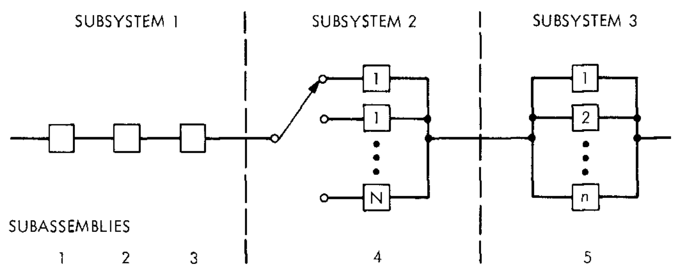

Fig. 2. Signal data path at a DSS