RELIABILITY ANALYSIS TO BALANCE COMPONENT REDUNDANCY WITH SPARES PRE-POSITIONING

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ABSTRACT

The purpose of this research was to examine the options of increasing overall system reliability of long range manned space missions by either adding redundant components, or by pre-positioning spares enroute. Using current NASA fault analysis techniques, component reliabilities can be calculated for each item contributing to the operation of a space mission. This paper discusses how this information may then be used to compare the costs between prepositioning missions and full redundant missions.

DISCLAIMER

The views expressed herein are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the United States Government.

INTRODUCTION

Historically, NASA has had to prepare two types of spacecraft for missions: unmanned long-range crafts and manned short-range crafts. Unmanned vehicles are engineered with the highest reliability possible since they are essentially "fire and forget." Manned vehicles, like the shuttle, do not need quite as high reliability since personnel are available to make repairs as necessary and shuttle missions are generally short. Instruments do not need to function for years at a time. They must operate for the mission and are generally refurbished during maintenance between missions.

The Future

As NASA looks toward extended space missions (Moon-Mars) an adjustment in our thinking is needed to design the ships to get us there. A ship carrying a crew to Mars and back will probably be one of the most complicated we have ever put into space. Chasing absolute reliability may prove to be a fiscally insurmountable task.

This paper examines prepositioning and redundancy to increase mission reliability for these kind of missions. This may solve many reliability issues allowing engineers to focus on reliability of items that can not be increased in this manner. We will discuss several route options for mission planning and then examine the increase in reliability by redundancy. In the end, we will demonstrate a logic that can be used to determine cost savings and discuss the tradeoffs observed.

ROUTES

By NASA policy, crew exposure to radiation in space should not result in effects exceeding acceptable risk levels [3, p. 3-39]. This mandates either a large increase in mass due to shielding for extended flights or a high-energy direct route mission profile to shorten exposure times. Unmanned missions do not have the same risk constraints. NASA has already demonstrated that unmanned spacecraft can withstand the rigors of deep space flight for extended periods and maintain full functionality. Additionally, it has been shown that the use of heteroclinic transfers can result in energy transfers between interplanetary bodies that are much lower than standard transfers [4].

The *Hohmann transfer orbit* is the minimum energy conic orbit for transfer between circular orbits [7, p. 66]. These transfers require two burns: the first to initiate the elliptic arc, and the second to merge with the desired orbit. Increases in velocity require more energy for both burns. Variations of this method can produce different mission profiles (energy and fuel consumption) that will be briefly discussed.

Planners refer to the highest energy mission as the "Short-stay" profile which allows about a one month stay. This mission minimizes the total mission time but requires the most energy. Not only is the crew exposed for an extended period but they are subject to increased radiation due to passing within Venus' orbit. The "Fast-transit" profile is a modification of the lowest energy transfer that utilizes additional fuel to shorten the trip. This type of mission requires a Δv in excess of 5 km/s. The final type of mission is the "long stay" mission and requires the least energy but exposes the astronauts the most [3, p. 3-37].

In addition to the Hohmann transfer methods are *heteroclinic transfers*. These are the low-energy transitions developed from the planar circular restricted three-body problem [4]. These types of transfers have been used successfully on several unmanned space mission. Estimates for transfers to Mars using this type of mission result in Δv values in the area of 3km/s or less [6]. This type of mission profile, however, has the longest and most variable transit times of all options.

The Δv/Mass Cost

The main differences between these options are the time of flight (ToF) and energy (Δv) required. Intuitively, we understand that sending mass on a longer, slower route should result in less energy. We will now examine this in detail in order to quantify the savings by using different flight profiles.

From the Tsiolkovsky rocket equation we determine the relationship between payload and fuel under similar conditions where Δv and u_{ex} (exhaust mass speed) are constant. Starting with the integrated form (1) we solve this equation for the relationship between the fuel mass, M_f, and the payload mass, M_p (2):

$$\Delta v = v_f - v_i = u_{ex} \ln\left(\frac{M_p + M_f}{M_p}\right) \text{ [7, p. 241]} \tag{1}$$

$$M_f = M_p e^{\left(\frac{\Delta v}{u_{ex}}\right)} - M_p \tag{2}$$

Since our initial conditions established Δv and u_{ex} to be constant (similar mission profile and vehicle) then the ratio the change in fuel mass with respect to a change in payload mass will be constant. We will refer to this as the fuel to payload ratio (FPR) for a given Δv and u_{ex}:

$$FPR = \frac{dM_f}{dM_p} = e^{\left(\frac{\Delta v}{u_{ex}}\right)} - 1 \tag{3}$$

Graphing the FPR vs. Δv we observe that the FPR increases faster with higher Δv.

RELIABILITY

NASA's Probabilistic Risk Assessment (PRA) Process

> PRA is a systematic, logical, and comprehensive discipline that uses tools like FMEA [Failure Modes and Effects Analysis], FTA [Fault Tree Analysis], Event Tree Analysis (ETA), Event Sequence Diagrams (EDS), Master Logic Diagrams (MLD), Reliability Block Diagrams (RBD), etc., to quantify risk. [2]

This tool list encompasses most of the tools available for risk analysis and reduction. One very useful tool is fault tree analysis (FTA). FTA requires the analyst to thoroughly examine the failure probabilities of every component [5] [8]. Hence, characterizing and quantifying failure rates are already built into the processes that NASA uses to analyze vehicles.

Redundancy

Implementing redundancy is a method to increase overall system reliability. A low level redundant system contains parallel components. High level redundant systems place the entire system in parallel with one or more identical systems [1, p. 87]. If "like" components with equivalent reliability are assumed, then the resulting reliabilities can be determined:

$$R_{low} = [1-(1-R)^2]^2 = [1-(1-2R+R^2)]^2 = (2R - R\ ) \ [1] \tag{4}$$

$$R_{high} = 1-(1-R^2)^2 = 1-[1-2R\ \ + R^4)] = 2R^2 - R^4 \ [1] \tag{5}$$

If *n* components are identical and independent, then the binomial pmf will determine the probability (*p*) that exactly *k* components won't fail during a specified period, *t*. From this, we can determine the probability that at least k components will not fail. This is the redundant system reliability (R_{sys}):

$$p(x) = \binom{n}{k} R^k (1-R)^{n-k} \tag{6}$$

$$R_{Sys} = \sum_{x=k}^{n} p(x) \tag{7}$$

ANALYSIS

Armed with the route information (Δv), component mass, and reliability estimates we can examine the cost in fuel of increasing system reliabilities by either prepositioning components or making them redundant on the primary vehicle. For simplicity we will define a few terms for the ensuing math:

A = total mass of the number of components necessary to meet minimum reliability standard of full-length mission = (no of components)*(mass of one component)

B = total mass of the number of components necessary to meet minimum reliability standard of half-length mission = (no of components)*(mass of one component)
H = FPR for high-energy flight (FPR_H), **L** = FPR for low-energy flight (FPR_L)

If we pursue redundancy only in the primary vehicle during the high-energy flight then the cost in fuel, $\mathbf{C_H}$, can be calculated as the product of the total component mass and the high-energy fuel-payload ratio. Similarly, the cost in fuel of prepositioning redundant components half-way through the mission, $\mathbf{C_L}$, can be calculated as the sum of the products of the total component mass for the half-length mission times the ratios FPR_L and FPR_H. The cost savings is calculated as the difference in these two scenarios.

$$C_H = AH \tag{8}$$

$$C_L = BH + BL = B(H + L) \tag{9}$$

$$Savings = C_H - C_L = AH - B(H + L) = (A - B)H - BL \tag{10}$$

Example

Consider the following components with Weibull failure distributions as stated [1, p. 183]:

Component	Scale Parameter θ, day	Shape Parameter β	250-day reliability	500-day reliability
Computer	1277.5	0.91	0.797207551	0.653203028
Avionic Mod	1460	0.8	0.783716474	0.654214361
Receiver	1095	1.8	0.932356455	0.783570919
Antenna	2190	1	0.892119443	0.7958771

Based on this failure data, reliability for the 250- and 500-day missions can be calculated. Assuming a minimum 99% reliability for the entire 500-day mission, we will have to incorporate redundancy into the systems. The tables below summarize the total number of components needed in each case:

	250-day mission		500-day mission	
Module	#of Components	Resultant Reliability	#of Components	Resultant Reliability
Computer	3	0.991660204	5	0.99498378
Avionic Mod	4	0.997811767	5	0.995056499
Receiver	2	0.995424354	4	0.997805871
Antenna	3	0.998744464	3	0.991494983

Now we examine the total mass to see where we may save fuel or increase overall reliability.

Mass (kg)	Component	B (kg)	B*L (kg)	A (kg)	A*H (kg)	B*H (kg)	Savings (kg)	Reliability Change
4	Computer	12	20.64	20	127.8	76.68	30.48	-0.0033236
3	Avionic Mod	12	20.64	15	95.85	76.68	-1.47	0.0027553
3	Receiver	6	10.32	12	76.68	38.34	28.02	-0.0023815
2	Antenna	6	10.32	6	38.34	38.34	-10.32	0.0072495

Using this data, planners can make informed decisions on the tradeoffs in order to sustain reliability. From our example we can observe that using prepositioning for the computer and the receiver components will achieve minimum reliability and require 58.5 kg (30.48 + 28.02) less fuel or allow 14 kg more of payload. Some modules may result in requiring more fuel by prepositioning. However, if the marginal increase in reliability is deemed beneficial, this may be acceptable.

Limitations

The logic used in this paper does not take into account increased reliability derived from components that survive the initial half of the mission. Depending on the individual failure distribution, surviving components *may* have considerable usefulness for the remainder of the mission. For this paper we assumed that all components would be replaced at the remote location. Additionally, consideration must be given to mission manpower tradeoffs to replace the components. The components chosen must not incur a resource demand that would limit the mission objectives. And finally, component for critical in-flight operations would be bad candidates for this logic since they should be configured to encompass possible abort returns that would potentially extend beyond the planned frame.

CONCLUSION

Use of pre-positioned stocks allows us to calculate the mission reliabilities based on shorter time frames. Instead of ensuring 99% reliability for a 500-day mission we can focus on a 99% reliability for two sequential 250-day missions. If we assume similar lift vehicles for the prepositioning mission and the manned mission, then the cost differentiator is based on the fuel savings between the two configurations.

Thorough examination of the potential tradeoffs between additional redundancy and prepositioning can create opportunities to lower mission cost or facilitate the inclusion of additional critical supplies not normally available due to mass-out constraints. Application over a large number of components may result in considerable savings.

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