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RELIABILITY IMPROVEMENT OF LOW EARTH ORBIT MICRO SATELLITE

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ABSTRACT

Satellite mass and reliability are two contradicting parameters affecting the satellite cost. To get a cost effective satellite, it would be necessary to compromise between low mass and high reliability**.** This challenge attracts the interest of many space institutions. This study presents an iterative simple technique to calculate and improve satellite reliability with low redundancy for the benefits of low mass. The failure contribution factor plays a strong role in the identification of the weak path which leads to system failure and propose the candidate component(s) to be duplicated. The present technique presents the failure contribution percentage of each component to satellite system failure and order them based on severity. Depending on the results the designer has to decide continue redundant or stop the process of improvement. The proposed technique had applied to a case study as a proof of concept. The work result shows how the proposed technique is simple and highly effective. More investigation will be applied to a real satellite project in the nearest future**.**

KEYWORDS

Reliability, Probability, Fault Tree, Cut-Set, Micro satellite platform

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INTRODUCTION

After World War I, reliability became one of the major interests of the aircraft industry, and attempts to improve reliability were pushed to the forefront. Lewis [1] defined reliability as the probability that a system will perform its intended function for a specified period of time under a given set of operating and environmental conditions. This universal definition can be applied to everything from very simple chips to the most complicated system, such as spacecraft. Spacecraft reliability is typically defined as the probability that a spacecraft will successfully complete its mission under expected conditions [2]. NASA has expended significant effort on improving the aerospace systems reliability and their cost effectiveness. Bean [3] discussed a statistical analysis of spacecraft reliability, on-orbit failures and spacecraft population. More recent studies have been revolved around specific spacecraft subsystems focused on failures in spacecraft power subsystems [4-5], solar array failures [6], and attitude control subsystem failures [7]. The comparative contribution of various subsystems to spacecraft on orbit failures has also been analyzed by Sperber[8] and Tafazoli [9]. Implementation of networks and redundancy modeling techniques are commonly used in reliability calculations. It is also known as reliability block diagrams, which provide a simple method to model a system of individual components [10].

Fault tree analysis (FTA) is another common reliability calculation technique used by conceptual designers. It is a top-down or deductive approach to reliability modeling. It uses logical gates and events to present the path of an accident through different steps, and hence a fault tree is constructed for the particular event [11-12]. The technical failures can be represented as a basic event while human errors can be represented as intermediate events that may intensify to become a technical failure [13].

Cut-set is the group of those elements or units, which will make the platform to fail, if their failure occurs. Determination of cut-set is an important step for both qualitative and quantitative analysis of a fault tree. A powerful tool for accomplishing this task is Boolean algebra, the algebra of sets and binary logic with only sentential connectives. The theory and application of Boolean algebra are described in Whitesitt [14]. The rules of Boolean algebra used in FTA are found in Vesely [15] and [16]. Backup techniques used as a solution to improve reliability of a system. Backup means including an identical component to the system that will take over if the original component fails. This backup technique is known as redundancy. It is a good solution for backing up inherently unreliable components that are essential to the success of the system [17].

In this paper we present formal modeling of platform micro satellite and logical specification of its reliability analysis.

RELIABILITY FAULT TREE AND CUT-SET MATHEMATICAL MODELS

Reliability

The reliability $R_i(t)$ of any component at any time t is given by [18-19]:

$$R_i(t) = e^{-\lambda t} \tag{1}$$

where **λ** is the state failure rate.

Probability of failure of an element can be as follows:

$$Qi(t) = 1 - Ri(t) = 1 - e^{-\lambda t} \tag{2}$$

Block diagram of a series set of components is shown in Fig. 1 (a and b) [20].

Fig. 1.a. block diagram

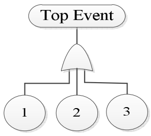

Fig. 1.b. Logical or gate

The reliability $R_s(t)$ of a series system of components has the following relationship [20]

$$R_s(t) = R_1(t) \times R_2(t) \ldots \ldots R_n(t) \tag{3}$$

$$R_s(t) = \prod_{i=1}^{n} R_i(t) \tag{4}$$

$R_i(t)$: Reliability of any component I, and n: number of component.

In a similar way the probability of failure $Q_s(t)$ of a series system is [18]:

$$Q_s(t) = 1 - \prod_{i-1}^{n} R_i(t) = 1 - \prod_{i-1}^{n}(1 - Q_i\,(t)) \tag{5}$$

Parallel connection of identical set of components is shown in Fig. 2 [20].

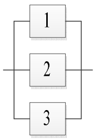

Fig. 2.a. block diagram

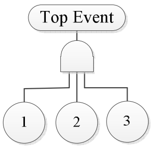

Fig. 2.b. Logical and gate

The reliability $R_p(t)$ of parallel system of components can be calculated as [18]:

$$R_p(t) = 1 - \prod_{i=1}^{n}\big(1 - R_i(t)\big) = 1 - \prod_{i=1}^{n} Q_i\,(t) \tag{6}$$

A special case of the parallel system is the *k* out of *n* system. It is shown in Fig. 3 (a and b)

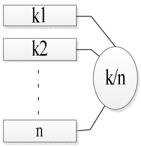

Fig. 3.a. block diagram

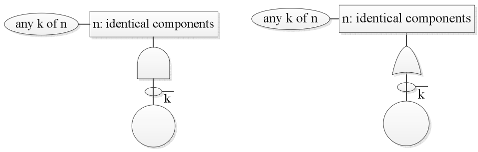

Fig. 3.b. Logical gates

Then, the reliability $R_s(t)$ is represented by [18]:

$$R_s(t) = \sum_{i=k}^{n} \binom{n}{i} \times [R(t)]^i \times [1 - R(t)]^{n-i} \tag{7}$$

Fault Tree

The fault tree analysis (FTA) is one of the most widely used methods in system reliability, maintainability and safety analysis. It is a deductive procedure used to determine the various combinations of hardware and software failures and human errors that could cause undesired events (referred to as top events) at the system level. The deductive analysis begins with a general conclusion, then attempts to determine the specific causes of the conclusion by constructing a logic diagram called a fault tree. This is also known as taking a top-down approach. The main purpose of the fault tree analysis is to help identify potential causes of system failures before the failures actually occur. It can also be used to evaluate the probability of the top event using analytical or statistical methods. These calculations involve system quantitative reliability and maintainability information, such as failure probability, failure rate and repair rate. After completing an FTA, efforts are focused on improving system safety and reliability. The basic symbols used in an FTA logic diagram are called logic gates which are similar to the symbols used by electronic circuit designers.

Cut-Sets derived from the Fault Tree and reduced by Boolean algebra, which is the smallest list of events that is necessary to cause the Top Event to happen. A listing of minimal cut sets is useful for design purposes by helping to determine the weakest links in the system. The algorithm used to identify minimum cut sets is based on the fact that AND gates always increase the size of a cut set while an OR gate always increases the number of cut sets. The OR gate represents the union of events at the gate. For event Q with two input events A and B attached to the OR gate, the probability is obtained as follows [15]:

$$P(Q) = P(A) + P(B) - P(A \cap B) \tag{8}$$

Because of $P(A \cap B)$ is small compared with $P(A) + P(B)$ for very low probability events, therefore,

$$P(Q) = P(A) + P(B) \tag{9}$$

The approximation of Eq. (9) is always a conservative estimate for the probability of event Q (because $P(A \cap B)$ is small compared with $P(A) + P(B)$ for very low probability events. Event Q will occur if any (at least) one of the input events to the OR gate occur. The AND gate represents the intersection of events at the gate. For event Q with two input events A and B attached to the AND gate, the probability is obtained as [15]:

$$P(Q) = P(A)P(B \mid A) = P(B)P(A \mid B) \tag{10}$$

If A and B are independent events then $P(B \mid A) = P(B)$ and $P(A \mid B) = P(A)$
Therefore:

$$P(Q) = P(A)P(B) \tag{11}$$

Cut-Set

From the previous equations:
Determination of system failure probability $\overline{Q}(t)$ under the assumption that component *i* is absolutely reliable

$$\overline{Q}(t) = Q_s(t) - q_i = 1 - \frac{R_s(t)}{R_i(t)} \tag{12}$$

Determination of contributions of any block set of components (Cut-sets (CFS)) in satellite failure:

$$CFS\ \% = \frac{Q_s(t) - \overline{Q}(t)}{Q_s(t)} \times 100 \tag{13}$$

The simplest and clearest way to explain the minimum cut set algorithm and its operation is illustrated in the following section. Let us consider the following example: The probability of failure Q(t) of the system component shown in Fig. 4 are presented in Table 1. The customer will never accept the system until its reliability is more than 90% after one year operation. The following necessary action is needed to improve the system reliability.

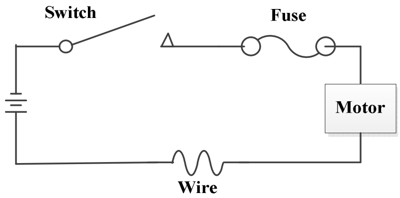

Fig. 4. Simple electrical motor circuit

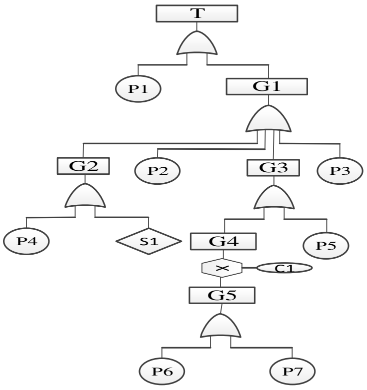

Fig. 5. Fault tree for the present example

Appendix-1 explains the top-down approach which leads to the top event T, therefore, contains 6 single component minimum cut sets and 2 double component minimum cut sets. Based on that the probability calculation for the simple motor circuit using the same notation as before is listed in Table 1.

Table 1. Probability of each basic event.

Event	Description	Q(t)
P1	Defect in motor	0.01
P2	Wire failure (open)	0.02
P3	Power supply failure	0.02
P4	Switch fails open	0.03
P5	Fuse failure	0.03
P6	Wire failure (shorted)	0.03
P7	Power failure (surge)	0.03
S1	Switch opened erroneously	0.07
C1	Fuse fails open	0.05

The probability Q(t) of failure of intermediate events can be evaluated using the fault tree. The probability of failure of the top event is given by the union of the minimum cut sets determined before as:

$$
\begin{aligned}
T &= P1 + P2 + P3 + P4 + S1 + P5 + (C1 \cdot P6) + (C1 \cdot P7) \\
&= 0.01 + 0.02 + 0.02 + 0.03 + 0.07 + 0.03 + \\
&\quad (0.05)(0.03) + (0.05)\,(0.03) = 0.183
\end{aligned}
$$

So, the system reliability is $R_T = 1.0 - 0.183 = 0.817$, this means that system reliability is less than required. So we will apply our proposed technique as follows:
The cut-set contribution factor plays the main idea in identification of the weak point of the path. The high contribution percentage means the high probability of failure. The cut-set contribution factor (CFS) is defined as the percentage of increasing of the system reliability if the first cut-set would be absolutely reliable.

Table 2 shows in column CFS1 the cut-set failure contribution factor calculated percentage for each event based on equations 12 and 13. Results presented in the column illustrates that S1 is the most critical element in system, which lead to system failure, so it is the candidate element to be redundant. Applying redundancy for $S1$ with $\grave{S}1$ as parallel set, Evaluation of system reliability and recalculation of failure contribution percentage factors for each component are shown in column CFS2 , then the calculated probability of failure Q(t) of the new system to be 0.123 , then the system reliability R(t) = 0.877. Repeat the calculation including P4 and P5 redundancy as shown in column CFS3 and CFS4 to increase reliability arriving to 0.917 which satisfy the customer requirement. Comparison of the components failure percentage contribution CFS's presented in Table 2. Illustrate clear identification of the most probable component affecting system failure.

Table 2. System reliability improvement.

No.	**Event**		**CFS1**	**CFS2**	**CFS3**	**CFS4**
	Event1	***Event 2***				
1	S1		36.62%	2.02%	2.76%	4.29%
2	P4		15.05%	24.95%	0.50%	0.78%
3	P5		15.05%	24.95%	34.08%	0.78%
4	P2		9.93%	16.46%	22.49%	34.88%
5	P3		9.93%	16.46%	22.49%	34.88%
6	P1		4.92%	8.15%	11.13%	17.26%
7	C1	P6	0.73%	1.21%	1.65%	2.56%
8	C1	P7	0.73%	1.21%	1.65%	2.56%
System Reliability			81.7%	87.7%	89.7%	91.7%

SATELLITE PLATFORM DESCRIPTION

Use of satellites for remote sensing applications has brought a revolution in this field, as they can provide information on a continuous basis of vast areas on the Earth's surface day and night. Most of the remote sensing satellites are operated in a low earth orbit (LEO orbit). Sun synchronous or low inclination angle orbits depend on the remote sensing mission requirements, revisit time and location of target. Micro satellite categorization is based on low mass, low power consumption, and low cost architecture requirements [21-22]. Generally, satellite consists of platform and payload; payload may be active or passive imaging system. Passive imaging payload depends on the reflection of sunlight rays from the surface of the target or the emitted energy from the target area. While the active consumes power for generating and emitting energy to the target area and receive the reflected energy. A general block diagram of micro satellite is presented in Fig. 6.

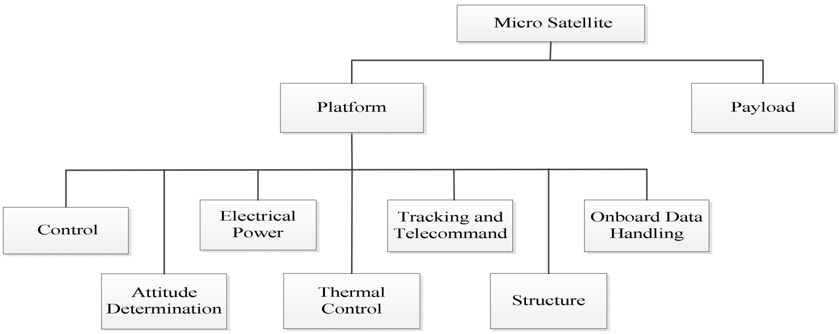

Fig. 6. Micro satellite block diagram

The present work considers that the satellite is composed of set of subsystems intended to perform defined function as described hereafter;

Payload

The payload is the part of the satellite that carries the desired instrumentation required for performing its intended mission. The nature of the payload on any satellite depends upon its mission requirements.

Platform

A platform is the vehicle or carrier accommodating remote sensors for which they are carried-out the mission. Remote sensing platforms are used to house sensors which obtain data for remote sensing purposes, and are classified according to their heights and events to be monitored. The model platform described in this paper contains 7 major subsystems, described as follows:

a) The control subsystem (Con)

The purpose of the control system is to orientate the main payload of the satellite to the target with the required accuracy; it controls and damping the system angular rates due to the satellite separation from launch vehicle. It also controls satellite stabilization. The main components in a control system are shown in Fig. 7.

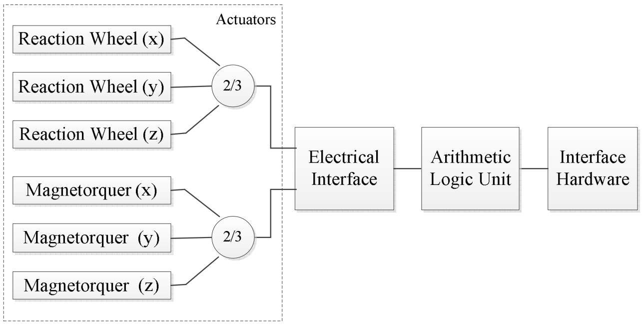

Fig. 7. Control subsystem (Con) block diagram.

b) Attitude determination subsystem (ATT)

The main function of an attitude determination subsystem is to determine the satellite orientation, and feedback the control system with the required data to perform its function, and prevent the satellite from tumbling in space. The main components of the attitude determination subsystem are shown in Fig. 8.

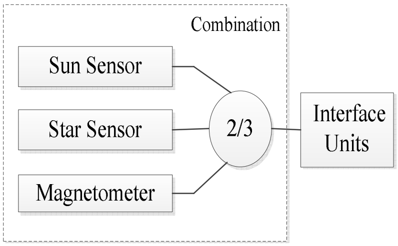

Fig. 8. Attitude determination (ATT) block diagram

c) Electrical Power subsystem (EP)

Power subsystem consists of three main elements: primary power source, secondary power source, and a power control and distribution network. These are shown schematically in Fig. 9.

Solar panels are the primary power system. It is an assembly of many thousand individual solar cells, connected in a suitable way to provide DC power levels from a few watts to tens of kilowatts.

Battery is the secondary power source. It provides power during periods when the primary one is not available. It acts as a back-up for a solar array. This means that batteries provide power during eclipses and that the solar array must recharge the batteries in sunlight.

Power control and distribution unit is also named power management, distribution and control unit. It operates with both primary and secondary power systems whose characteristics are changing with time.

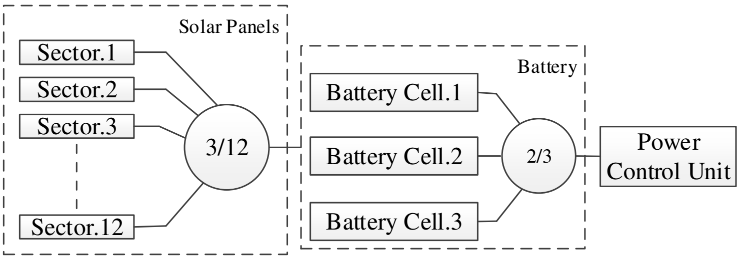

Fig. 9. Electrical Power (EP) Block Diagram

d) Telemetry Tracking and Command (TT&C) subsystem

The Telemetry Tracking and Command(TT&C) subsystem is intended for monitoring satellite conditions right after the separation from the launch vehicle to the end of its operational life in space. The tracking part of the subsystem determines the position of the spacecraft and records its travel using angle, range and velocity information. The telemetry part gathers information on the health of various subsystems of the satellite. It encodes this information and then transmits it to the ground mission control center. The command element receives and executes remote control commands from the ground control center to effect changes on the platform functions, configuration, position and velocity [23]. Block diagram of TT&C is shown in Fig.10.

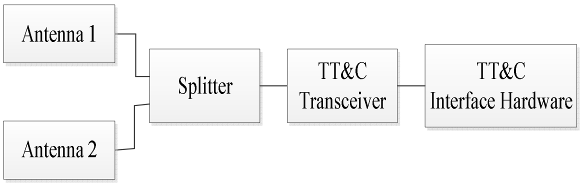

Fig. 10. Telemetry tracking and command (TT&C) block diagram.

e) Onboard computer (OBC)

The on-board computer is the central control unit for processing and managing the mission data on the satellite board. In some cases satellites incorporate more than one computer system to fulfill different specific tasks. Figure 11 shows a simplified block diagram of the main components in onboard computer subsystem.

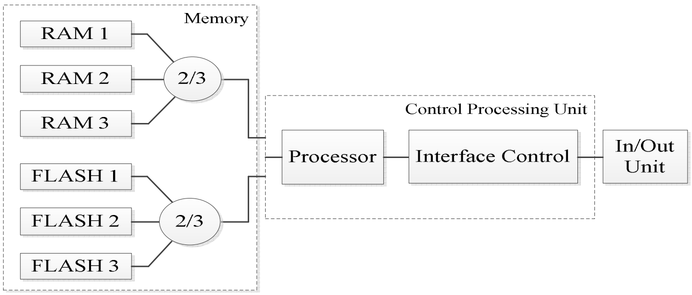

Fig. 11. Onboard Data Handling (OBDH) block diagram.

f) Structure and Mechanisms subsystem (SM)

Satellite structural is based upon design with a strong emphasis upon minimum weight. Vibration interaction and material selection should be taken into considerations for space use. The major goals of minimum mass and maximum reliability must be met with minimum cost and schedule. The structure should satisfy the mission requirements as well as the launch vehicle requirements. Also, it should withstand the handling and ground transportation loads. It accommodates the satellite components in the right operation position and keep their orientation at within the permissible relative orientation error.

Satellite usually contains mechanisms, which perform functions essential to their operation. These mechanisms often have a single point failure. So the structure mechanism has to be designed rigid enough, to prevent any frequently catastrophic failure. In this sense reliability almost equal one.

g) Thermal control subsystem (TSS)

Satellite thermal control subsystem is designed for controlling the satellite components and structural temperatures. Satellite equipment is designed to operate most effectively at or around room temperature. This control needed for two main reasons: (1) electronic and mechanical equipment usually operate efficiently and reliably only within relatively narrow temperature ranges and (2) most materials have non-zero coefficients of thermal expansion and hence temperature changes imply thermal distortion.

Thermal control subsystem is either passive or active [23]. In our case Passive thermal control techniques is proposed, which consist essentially of the selection of surface properties, control of conduction paths, thermal capacities and the use of insulation systems. Reliability for passive thermal control almost equal one.

PLATFORM RELIABILITY AND FAULT TREE ANALYSIS

Reliability

In reliability theory, mechanical components are assumed to have Poisson distribution; while the reliability of electrical components has exponential distribution throughout these study components are assumed to have constant failure rates. Reliability data of the satellite platform equipment are presented in Table 3. This table contains the subsystem composition, its architecture and abbreviations for subsystems and components. Also the reliability mathematical model is used to identify weak links, and indicates where reliability improvement activities should be introduced. The platform reliability is calculated using reliability values listed in Table.3, and is using mathematical equations (1, 4, 6 and 7). For the proposed platform block diagram presented in the previous Fig. (7-11), Reliability of each subsystem is calculated and presented in Table 4.

Table 3. Platform equipment reliability parameters.

No.	Component Name	Abb.	R(t)	No.	Component Name	Abb.	R(t)
1	Reaction Wheel	RW	0.978	26	Pin	CP	0.998
2	Magnetorquer	MQ	0.977	27	Constrand String	SCS	0.997
3	Control Software	SC	0.989	28	Connector Interface	SCI	0.997
4	Electrical Interface	EI	0.998	29	Power Control Unit	PCU	0.998
5	Arithmetic Logic Unit	ALU	0.988	30	Ant1. Hardware	AA1	0.976
6	Interface Hardware	IH	0.998	31	Ant1.Connection	AC1	0.998
7	Navigation Software	NS	0.989	32	Ant1.deployed	AN1	0.986
8	Sun Sensor	SUN	0.989	33	Ant2. Hardware	AA2	0.975
9	Star Sensor	STR	0.989	34	Ant2.Connection	AC2	0.997
10	Magnetometer	MAG	0.989	35	Ant2.deployed	AN2	0.985
11	Sun Sensor Hardware	SUH	0.976	36	Splitter	SP	0.986
12	Sun Sensor Interface	SUI	0.998	37	TT&C Transceiver	Trans	0.997
13	Sun Sensor Software	SUS	0.989	38	TT&C Interface Hardware	IHC	0.989
14	Star Sensor Hardware	STH	0.975	39	RAM.1	R1	0.996
15	Star Sensor Interface	STI	0.997	40	RAM.2	R2	0.996
16	Star Sensor Software	SIS	0.979	41	RAM.3	R3	0.996
17	Magnetometer Hardware	MAH	0.977	42	FLASH.1	F1	0.995
18	Magnetometer Interface	MAI	0.997	43	FLASH.2	F2	0.995
19	Magnetometer Software	MAS	0.989	44	FLASH.3	F3	0.995
20	Interface Unit	IU	0.998	45	Processor	PC	0.998
21	Solar panel Sector	S	0.978	46	Interface Control	IC	0.999
22	Battery Cell.1	B1	0.995	47	In/Out Unit	IOU	0.989
23	Battery Cell.2	B2	0.995	48	Computer Software	SO	0.989
24	Battery Cell.3	B3	0.995	49	Structure and Mechanisms	SM	0.9999
25	Cable Connector interface	CCI	0.998	50	Thermal subsystem	TSS	0.9999

Table 4. Platform subsystems reliability parameters.

Subsystem	R(t)
Con	0.983
ATT	0.987
EP	0.997
TT&C	0.972
OBC	0.985
SM	0.9999
TSS	0.9999
Total Platform	0.925

Contributions Factor Calculation

The proposed satellite platform has been analyzed and its fault tree is presented in Fig. 12. The construction procedure of list matrix ended whenever all its elements are basic events. The results show that each row of the list matrix corresponds to cut-set. The result analysis of the proposed satellite platform is presented in Table 5 and 6.

Table 5 presents the single element cut-set component and its contribution percentage in failure for satellite platform system; this table shows in column CFS the failure contribution factor calculated percentage for each event in satellite platform based on equations 12 and 13. Results presented in the column indicate that splitter (SP) is the most critical element in system, which lead to system failure with probability 14.38%, followed by different components ALU, SC…etc.So, it is the candidate element to be redundant seriously to increase reliability to arrive to satisfy the customer requirement.

Table 5. Single element cut set percentage for satellite platform.

No.	Component	CFS
1	SP	14.38%
2	ALU	12.31%
3	SC	11.27%
4	NS	11.27%
5	IHC	11.27%
6	IOU	11.27%
7	SO	11.27%
8	Trans	3.05%
9	IH	2.03%
10	PCU	2.03%
11	PC	2.03%
12	IC	1.02%

Table 6 presents the double element cut-set and their percentage for satellite platform system failure, which means that components SUH & STH together has a cut-set contribution factor equal to 0.37%, which means that we need to implement the redundant system for both component at the same time.

Table 6. Double Element Cut Set Percentage for Satellite Platform.

No.	Component # 1	Component # 2	CFS	No.	Component # 1	Component # 2	CFS
1	SUH	STH	0.37%	15	AN1	AN2	0.13%
2	AA1	AA2	0.37%	16	SUS	MAS	0.08%
3	STH	MAH	0.35%	17	STH	MAI	0.05%
4	SUH	MAH	0.34%	18	SUH	STI	0.04%
5	SUH	STS	0.31%	19	SUH	MAI	0.04%
6	STS	MAH	0.3%	20	AA1	AC2	0.04%
7	AA1	AN2	0.22%	21	ST1	MAH	0.04%
8	AN1	AA2	0.22%	22	STS	MAI	0.04%
9	SUS	STH	0.18%	23	SUI	STH	0.03%
10	SUS	MAH	0.17%	24	AC1	AA2	0.03%
11	STH	MAS	0.17%	25	SUI	MAH	0.03%
12	SUH	MAS	0.16%	26	SUI	STS	0.03%
13	SUS	STS	0.15%	27	AN1	AC2	0.03%
14	STS	MAS	0.14%	28	SUS	STI	0.02%

CONCLUSION

The mass of the satellite platform depends on the mass of the mounted subsystems. Reliability of the satellite platform system depends on the system redundancy. An effective procedure to evaluate the satellite platform reliability under the condition of minimum mass has been developed. Fault tree plays a strong rule in defining the weakest link, and the cut set contribution factor defines the candidate component to be redundant. Instead of augment the system with a parallel complete subsystem as redundant include a parallel set of components to that set in the weak path.

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APPENDIX A

The solution of top-down approach which leads to the top event T is as follows:

Let T denote the top event
Let P denote primary events (circles)
Let G denote intermediate events (rectangles)
Let S denote undeveloped events (diamonds)
Let C denote conditioning events (ovals)

The fault tree of the proposed example is constructed starting from the top. Identification of the main contributing events, including all events and scenarios that may cause the top event are the basis for building the system fault tree presented in Fig. 5.

Therefore;
T = motor fails to operate
P1 = defect in motor
P2 = wire failure (open)
P3 = power supply failure
P4 = switch fails open
P5 = fuse failure under normal conditions (open)
P6 = wire failure (shorted)
P7 = power failure (surge)
G1 = no current to motor
G2 = switch fails open
G3 = fuse open
G4 = fuse failure due to overload
G5 = overload in circuit
S1 = switch opened erroneously
C1 = fuse fails to open

The following are the equations for each gate of the tree:
$T = P1 + G1$
$G1 = P2 + P3 + G2 + G3$
$G2 = P4 + S1$
$G3 = G4 + P5$
$G4 = C1 \cdot G5$
$G5 = P6 + P7$

Using the top-down approach we get by substitution:

$$\begin{aligned}
T &= P1 + G1 \\
&= P1 + P2 + P3 + G2 + G3 \\
&= P1 + P2 + P3 + P4 + S1 + G3 \\
&= P1 + P2 + P3 + P4 + S1 + G4 + P5 \\
&= P1 + P2 + P3 + P4 + S1 + (C1 \cdot G5) + P5 \\
&= P1 + P2 + P3 + P4 + S1 + P5 + C1 \cdot (P6 + P7) \\
&= P1 + P2 + P3 + P4 + S1 + P5 + (C1 \cdot P6) + (C1 \cdot P7)
\end{aligned}$$

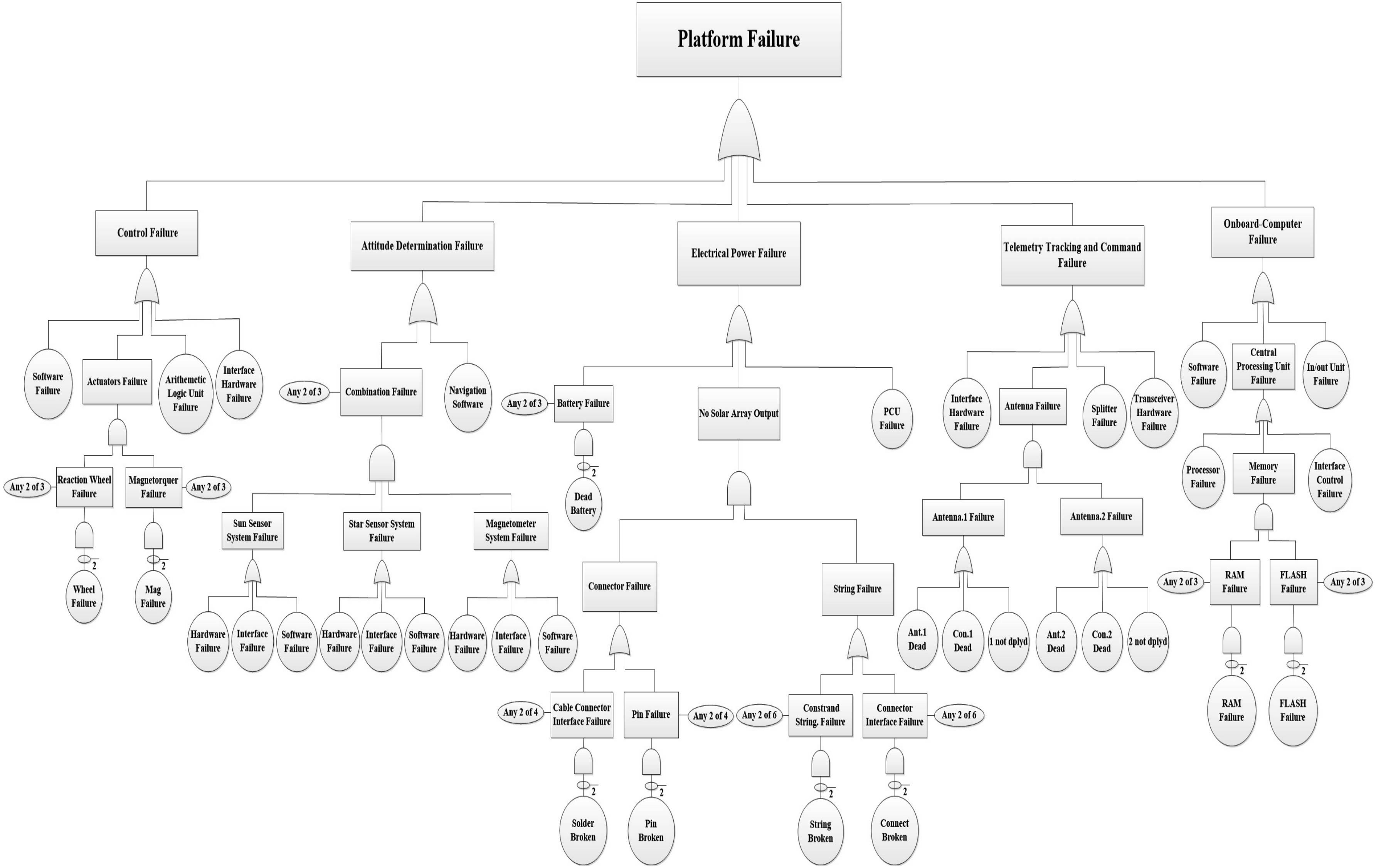

Fig. 12. Fault Tree for the Proposed Satellite Platform