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# Reliability analysis of the solar array based on Fault Tree Analysis

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**Abstract.** The solar array is an important device used in the spacecraft, which influences the quality of in-orbit operation of the spacecraft and even the launches. This paper analyzes the reliability of the mechanical system and certifies the most vital subsystem of the solar array. The fault tree analysis (FTA) model is established according to the operating process of the mechanical system based on DFH-3 satellite; the logical expression of the top event is obtained by Boolean algebra and the reliability of the solar array is calculated. The conclusion shows that the hinges are the most vital links between the solar arrays. By analyzing the structure importance(SI) of the hinge's FTA model, some fatal causes, including faults of the seal, insufficient torque of the locking spring, temperature in space, and friction force, can be identified. Damage is the initial stage of the fault, so limiting damage is significant to prevent faults. Furthermore, recommendations for improving reliability associated with damage limitation are discussed, which can be used for the redesigning of the solar array and the reliability growth planning.

## 1. Introduction

Solar arrays are one of the most vital links to satellite and other spacecraft mission success. Over the last 10 years, Airclaim's Ascend SpaceTrak database has documented 117 satellites solar array anomalies, 12 of which resulted in the failure of the satellite [1-2]. The solar array anomalies have made up 33 percent of all insurance claims in the last 10 years, which covers a large proportion of all the events [1]. Therefore, it is of great importance for the designers to know the causes of different faults and how to improve the reliability of the solar arrays.

Although the faults have decreased in the last few years by some measures, they still affect the longevity of the satellites severely [2]. The faults of the mechanical system may occupy a large proportion of all the faults [2-5]. Henry discussed the recommendations for improving the reliability in many aspects based on one certain database while he did not discuss the issue of the reliability analysis [2]. Yuan presented one reliability model in which all of the faults are in a series of connection system and the probabilities of the faults obey exponential distributions [6]. Xiao proposed a reliability analysis method of the deployable mechanism in solar arrays,

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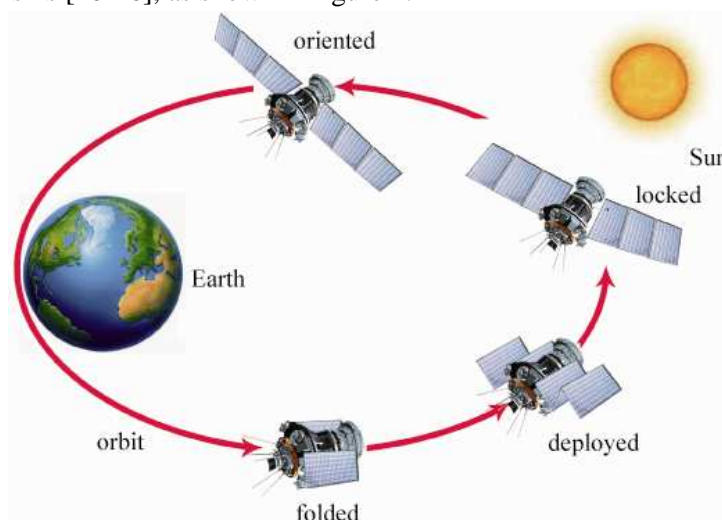
performed the reliability analysis based on fault tree analysis (FTA), and gave some suggestions to eliminate faults [7].

Nevertheless, there are some issues that are not well-addressed in the previous studies. Firstly, many papers focused mostly on the electric and electronic system of the solar array [8, 9]; however, the mechanical system of the solar array which is also significant may be frequently ignored. Secondly, it is noted that the causes of failure have close relationship with the subsystems of the mechanical system. Consequently, identifying the weak subsystem of the solar array is very important for the reliability growth planning and reliability allocation. However, the previous literatures have just researched on the causes of the failure in the solar array which are distributed discretely in the mechanical system [2, 6, 7]. To our best knowledge, the reliability analysis of the important subsystems of the solar array is still lacking. Our paper analyzed the causes of the failure of the solar array by FTA, identified the most vital mechanical subsystem and put propositions to improve the reliability of the main system and the vital subsystem. The faults caused by damage accumulation and the propositions associated with damage limitation are especially considered in the paper.

The remainder of this paper is organized as follows. In Section 2, the mechanical system of the solar array is introduced. Reliability analysis of the mechanical system and the hinges are given in Section 3 and Section 4 respectively. The last section is the conclusion of the paper.

## 2. Mechanical system of the solar array

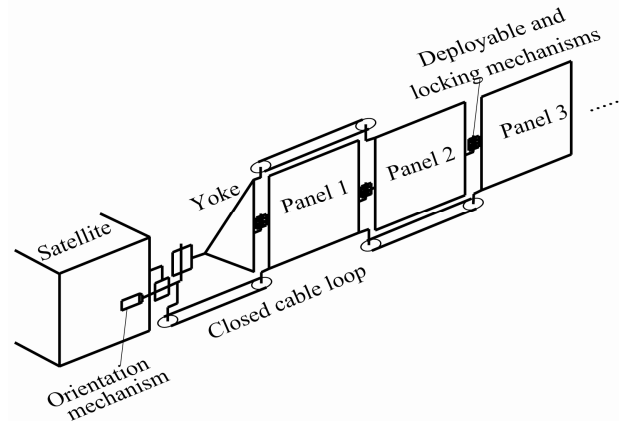
Solar arrays are widely used in the spacecraft nowadays, which is originally folded, deployed and locked in the orbit and oriented to the sun, as shown in figure 1. The mechanical system consists of 6 kinds of mechanisms [10-16], as shown in figure 2.



**Figure 1.** The principle of deployable solar array performance

The driving mechanism provides energy to stretch the solar arrays in the form of force or torque. The two main forms are employed to perform deployment of the solar arrays: driven by motor(s) or torsion springs. The deployable mechanism can be used between panels. As the space environment is severe and changeable, designers always prefer to choose simple hinges with clearances to improve the reliability of the structure. The synchronization mechanism keeps the

synchronization of different panels avoiding interference. The closed cable loop (CCL) is often used as the synchronization mechanism. The solar array is locked by the locking mechanism. Finally, the orientation mechanism keeps the position to ensure the normal incidence of the sun light, which contains the orientation driving mechanism, the orientation transmission mechanism and orientation executive mechanism. The other mechanisms include some measuring devices like the angular sensors, the temperature sensors, and so on.



**Figure 2.** The mechanisms of the solar array

### 3. Reliability analysis of the mechanical system

#### 3.1. FTA model

FTA was originated from the Bell Telephone Laboratories in 1962, which uses logical and image symbols to do qualitative and quantitative analysis of systems [17-18]. The fault tree of the solar array are established according to the past performance data [1, 2, 4, 5, 9]. This paper focuses on the Satellite DFH-3, launched by PRC on May 12, 1997. The faults are summarized on the basis of the working process of the solar array. Figure 3 shows the fault tree of the mechanical system. All of the events are connected by the logical symbols, AND gate and OR gate. Table 1 represents the markers and the faults in figure 3.

#### 3.2. Analysis based on FTA model

In FTA analysis, Boolean algebra is commonly used to simplify the formula, getting the expression of the top event. So if the fault probability of each unit is acquired, the fault probability of the whole system can be instantly obtained. The Boolean logical expression of the failure is:

$$TF = \sum_{i=1}^5 F_i = \sum_{i=1}^3 S_i + \sum_{i=5}^8 S_i + \sum_{i=13}^{15} S_i + \sum_{i=1}^3 T_i + T_6 + \sum_{i=8}^{11} T_i + \sum_{i=14}^{15} T_i + \sum_{i=1}^3 M_i + \sum_{i=5}^{12} M_i + F_{11} + F_{12} \quad (1)$$

where the symbol  $\Sigma$  denotes the Boolean addition.

Assuming that the root faults of the system are independent of each other and the probability of the top event (fault probability of system) can be obtained as

$$P(TF) = P\left(\sum_{i=1}^3 S_i + \sum_{i=5}^8 S_i + \sum_{i=13}^{15} S_i + \sum_{i=1}^3 T_i + T_6 + \sum_{i=8}^{11} T_i + \sum_{i=14}^{15} T_i + \sum_{i=1}^3 M_i + \sum_{i=5}^{12} M_i + F_{11} + F_{12}\right) \quad (2)$$

Equation (2) can be expressed as follows (table 1):

$$P(T) = P\left(\sum_{i=1}^{33} G_i\right) - \sum_i P(G_i G_j) + \dots + (-1)^{n-1} P(G_1 G_2 \dots G_n) \quad (n=1, 2, \dots, 33) \quad (3)$$

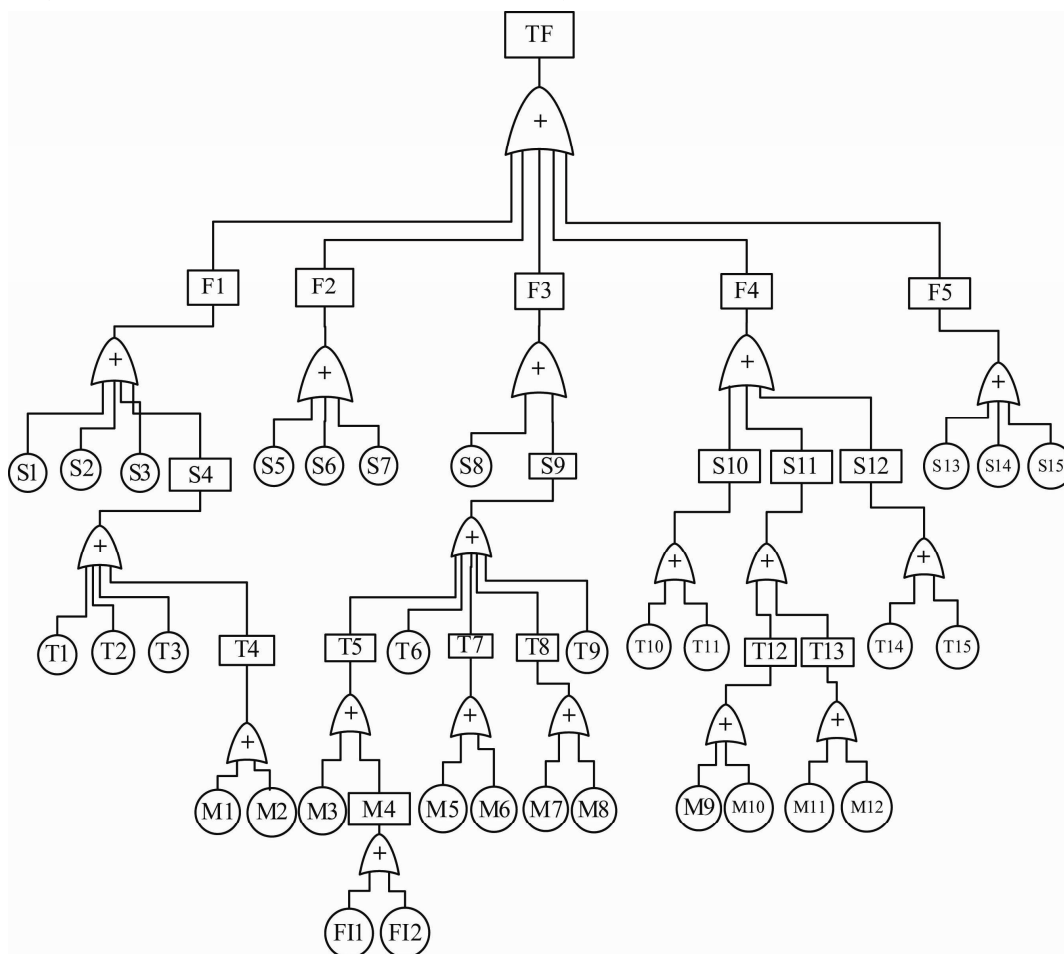
The reliability probability of the system can be computed by

$$R(T) = 1 - P(T) \tag{4}$$

Reference [19] has pointed out that equation (3) have  $(2^{33} - 1)$  terms. When the number of minimal cut sets goes up to a certain extent, combinatorial explosion will occur. The FTA model owns 33 root faults, which will also result in expensive computation. If this system is refined further, the parameter  $n$  will be larger and the calculation time will be longer, even beyond the calculation ability of one certain personal computer. To avoid this, equation (3) can be changed into:

$$P(T) = P(G_1 + \bar{G}_1 G_2 + \bar{G}_1 \bar{G}_2 G_3 + \dots \bar{G}_1 \bar{G}_2 \bar{G}_3 \dots G_{33}) = P(G_1) + P(\bar{G}_1 G_2) + \dots P(\bar{G}_1 \bar{G}_2 \bar{G}_3 \dots G_{33}) \tag{5}$$

From figure 3, it is clear that AND gate is the only logical symbol in the model. As a result, every fault in the model can lead to the fault of the system. The structure importance (SI) is usually used to measure the properties of all the root faults in the fault tree. With exhaustive method, the SI of all the root faults can be obtained, which is the same as 3.0300%.



**Figure 3.** FTA model of the mechanical system

**Table 1.** Markers and the faults of the solar array

Marker	New marker	Fault	Marker	New marker	Fault
TF	-	The failure of the solar array in deployment	$T_5$	-	Deadlocking in the deployable structures
$F_1$	-	The faults during the orientation process	$T_6$	$G_{14}$	Insufficient preload of the torsion spring
$F_2$	-	The faults during the unlocking process	$T_7$	-	The insufficient preload of the CCL
$F_3$	-	The faults during the	$T_8$	$G_{15}$	The high friction

		deployment process			coefficient
$F_4$	–	The faults during the locking process	$T_9$	$G_{16}$	The fractures of the CCL
$F_5$	–	The other faults	$T_{10}$	$G_{17}$	The locking hole is out of shape by the deformation of the solar array
$S_1$	$G_1$	The exhaustion of energy in the battery	$T_{11}$	$G_{18}$	The deformation of the caging pin
$S_2$	$G_2$	The fault of the photosensor	$T_{12}$	–	The fault of the caging pin
$S_3$	$G_3$	The fault of the control system	$T_{13}$	–	The fault of the spring
$S_4$	–	The fault of the orientation stepping motor	$T_{14}$	$G_{19}$	The deformation of the baffle
$S_5$	$G_4$	The fault of the electronic arcing	$T_{15}$	$G_{20}$	The fracture of the baffle
$S_6$	$G_5$	The fault of the cutter	$M_1$	$G_{21}$	The fault of the harmonic reducer
$S_7$	$G_6$	Man's misoperation	$M_2$	$G_{22}$	Fault in the gears
$S_8$	$G_7$	Deadlocking in the trip mechanism	$M_3$	$G_{23}$	Deadlocking in hinges
$S_9$	–	The fault of the solar array that it cannot be deployed to the right position	$M_4$	–	Deadlocking in CCL
$S_{10}$	–	Deadlocking of the caging pin	$M_5$	$G_{24}$	The insufficient of the preload of the CCL
$S_{11}$	–	The fault in the locking mechanism	$M_6$	$G_{25}$	Deformation of the CCL
$S_{12}$	–	The fault of the baffle	$M_7$	$G_{26}$	The fault of the structure caused by the particles in space
$S_{13}$	$G_8$	Impact caused by particles in space	$M_8$	$G_{27}$	The fault of the lubricant
$S_{14}$	$G_9$	Vibration caused by clearances between hinges	$M_9$	$G_{28}$	Fracture of the caging pin
$S_{15}$	$G_{10}$	Thermal deformation of the solar panel	$M_{10}$	$G_{29}$	The deformation of the caging pin
$T_1$	$G_{11}$	The disordered pulse signal	$M_{11}$	$G_{30}$	The spring cannot provide enough torque
$T_2$	$G_{12}$	The fault in the mechanical part of the motor	$M_{12}$	$G_{31}$	The fracture of the spring
$T_3$	$G_{13}$	The electronic fault of the motor	$FI_1$	$G_{32}$	The slip of the cables
$T_4$	–	The fault in the transmission system	$FI_2$	$G_{33}$	Deadlocking in the wheel

For the high cost of mechanical systems, it is extremely difficult to implement conventional

reliability tests. Therefore, previous operation data documented by the SpaceTrak Database and engineering experience can be used to get the reliability data of the solar array [1]. Reference [20] presents the relationship between the reliability of the satellite and its operation time by analyzing fault times of the satellites launched between January 1990 and October 2008. Weibull distributions are used to model the reliability of satellites.

According to the characteristics of the faults in the system, table 2 demonstrates the linguistic variables, ranks and the fault time on the basis of the engineering experience. Take the second column of table 2 as an example. The probability of the fault is very high and the fault time corresponding to the rank I is 14.2560 years with the reliability 0.8983. Table 3 shows the markers and their ranks based on engineering experience and operation data.

**Table 2.** Solar array classification ranks of the fault model

Linguistic Variable (Probability of fault)	VH (Very High)	H (High)	FH (Fairly High)	M (Medium)	FL (Fairly Low)	L (Low)	VL (Very Low)
Ranks of mechanical faults	VII	VI	V	IV	III	II	I
The fault time (years)	14.2560	7.3977	5.0267	2.1547	0.6489	0.1752	0.0027
Reliability	0.8983	0.9322	0.9496	0.9633	0.9747	0.9852	0.9975

**Table 3.** Markers and ranks

Markers	Ranks	Markers	Ranks	Markers	Ranks	Markers	Ranks
$G_1$	II	$G_{10}$	VI	$G_{19}$	IV	$G_{28}$	II
$G_2$	I	$G_{11}$	II	$G_{20}$	III	$G_{29}$	V
$G_3$	III	$G_{12}$	II	$G_{21}$	II	$G_{30}$	V
$G_4$	II	$G_{13}$	II	$G_{22}$	II	$G_{31}$	I
$G_5$	II	$G_{14}$	V	$G_{23}$	VI	$G_{32}$	I
$G_6$	I	$G_{15}$	V	$G_{24}$	V	$G_{33}$	I
$G_7$	IV	$G_{16}$	IV	$G_{25}$	V		
$G_8$	VI	$G_{17}$	VL	$G_{26}$	VI		
$G_9$	VII	$G_{18}$	V	$G_{27}$	V		

The fault probability of the solar array according to equation (5) is

$$P(TF) = 0.1952 \quad (6)$$

And the reliability of the system is

$$R(TF) = 1 - P(TF) = 0.8048 \quad (7)$$

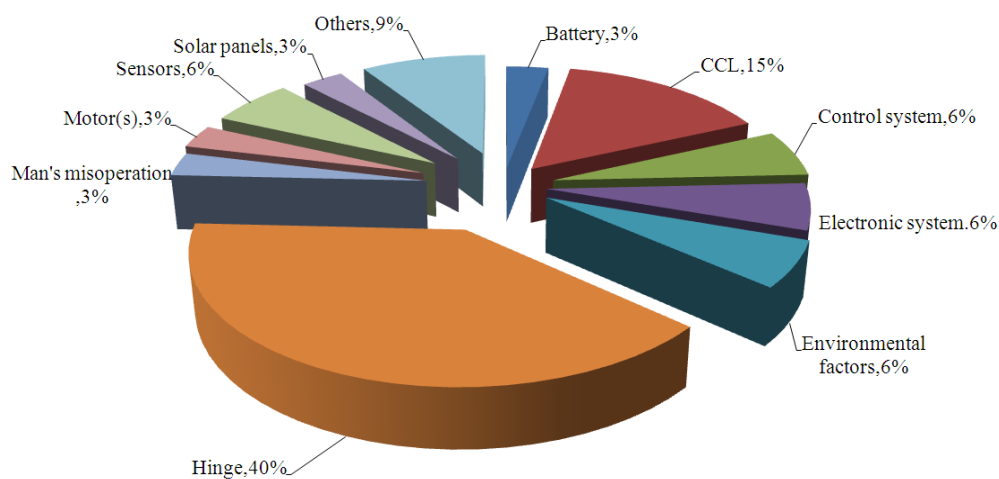
By analyzing the FTA model, the reliability of the solar array is 0.8048. Table 4 demonstrates the recommendations and improvement measures of the dangerous faults with the rank over V, which can be used as references to designers. According to table 1, the 14 faults are associated with hinges' disorder, most of which own the ranks over V. For instance, deadlocking in hinges and the fault of the lubricant own the ranks VI and V respectively, which may lead to the failure of the hinge according to the above results. Figure 4 shows the faults in solar array with different proportions, 40% of which are related to the hinge.

During the deployment, the hinges are the most vital subsystems in the solar arrays. So it is essential to analyze the reliability of the hinge so as to get the failure mechanism of the hinge.



**Table 4.** Root faults and improvement measures (solar array)

Root faults	Contents	Improvement Measures
$G_{10}$	Thermal deformation of the solar panel	Use new material that is fit for the change of temperature in space; research on the mechanisms of thermal damage on solar array in space; develop appropriate standard for the accumulation of damage.
$G_{17}$	The locking hole is out of shape by the deformation of the solar array	Control the deformation by using new materials; optimize the mechanical structures of the hinge.
$G_{23}$	Deadlocking in hinges	Improve the lubrication conditions; conduct experiments on the hinges under different conditions similar to the space environment.
$G_{26}$	The fault of the structure caused by the particles in space	Increase the strength of the materials; shift the orbit around the earth to avoid being influenced; research on the damage caused by the impact of different sizes of particles with different velocities to obtain the failure criterion.

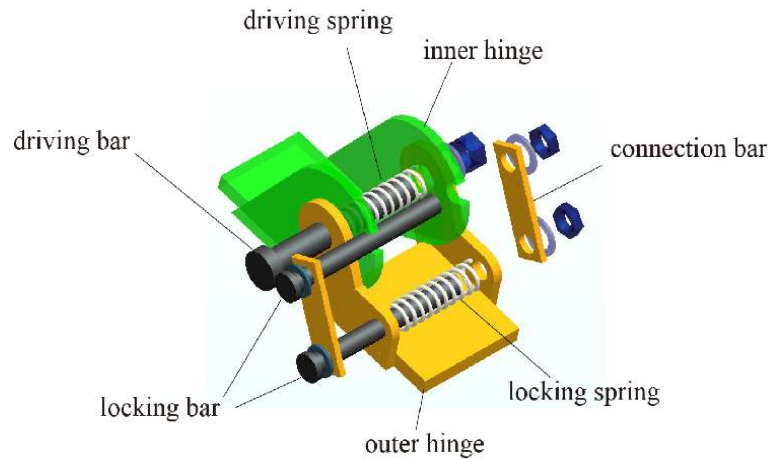
**Figure 4.** Faults in solar array

## 4. Reliability analysis of the hinge

### 4.1. FTA model of the hinge

The hinges between the panels of the solar array rotates when the arrays deploy. A typical type [8] is introduced to model the fault tree. The hinge mainly includes the inner hinge, outer hinge, driving bar, locking bar, connection bar, driving spring and locking spring (figure 5). The inner hinge has one groove for the locking bar to insert. The driving spring makes the inner and outer hinges rotate around the axis of the driving bar after release. The hinge is locked by the locking bar which is driven by the locking spring.

The faults are described in table 5 and figure 6 shows the FTA model of the hinge. The FTA model contains 5 layers. Subsystem redundancy is widely used in the aerospace engineering for higher reliability [19]. In fact, there is a backup driving spring for use lest the main driving spring be out of service [8]. In the FTA model,  $T_1$  and  $T_2$  represent the fault of the main and backup springs.

**Figure 5.** Mechanical structure of the hinge**Table 5.** Markers and the faults of the hinge

Marker	Faults	Marker	Faults
TF	The fault in the hinge	$T_4$	Cold welding in space between the driving bar and the hole
$F_1$	Deadlocking of the hinge	$T_5$	The fault of the lubricant
$F_2$	The fault of locking	$T_6$	The insufficient torque of the locking spring
$S_1$	The fault of the driving spring	$T_7$	The changeable temperature (harsh thermal environment)
$S_2$	The fault of the caging spin	$M_1$	The insufficient torque of the main driving spring
$S_3$	The high friction force	$M_2$	The insufficient torque of the backup driving spring
$S_4$	The fault of the locking spring	$M_3$	The bad characteristic of the material
$T_1$	The fault of the main driving spring	$M_4$	The bad characteristics of the lubricant
$T_2$	The fault of the backup driving spring	$M_5$	The fault of the seal
$T_3$	The caging pin cannot insert into the hole	$M_6$	The fault of the lubricant

#### 4.2. Analysis based on FTA model of the hinge

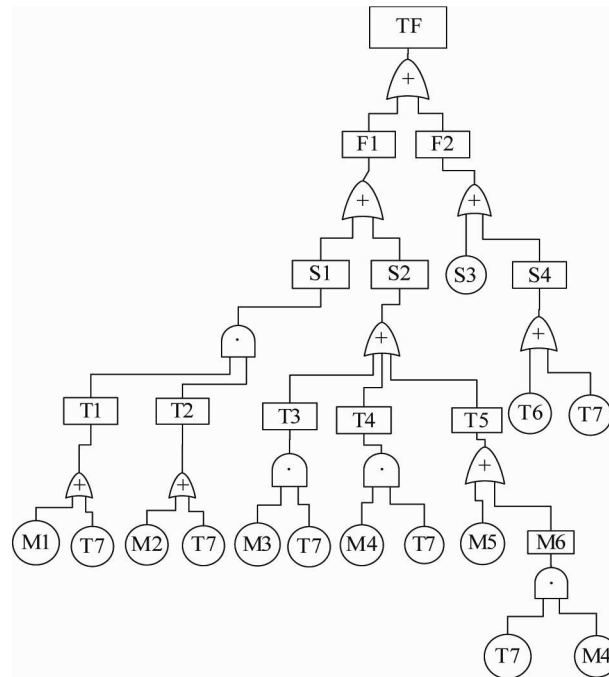
The Boolean logical expression of the top fault is:

$$\begin{aligned}
 TF &= M_1 \cdot M_2 + M_1 \cdot T_7 + M_2 \cdot T_7 + T_7 + M_3 \cdot T_7 + M_4 \cdot T_7 + M_5 + T_6 + T_7 + S_3 \\
 &= M_1 \cdot M_2 + M_5 + T_6 + T_7 + S_3
 \end{aligned}
 \quad (8)$$

where the symbols  $\Sigma$  and  $\cdot$  are the Boolean addition and Boolean multiplication respectively. Assuming that the root faults of the system are independent of each other, so the probability of the top event (probability of system fault) is:

$$P(TF) = P(M_1 \cdot M_2 + M_5 + T_6 + T_7 + S_3)
 \quad (9)$$

According to equation (5), equation (9) can be calculated on the assumption that all the faults are independent each other. Table 6 presents the SI of all the root faults with exhaustive method.



**Figure 6.** FTA model of the hinge

**Table 6.** SI of the root faults

Root faults	SI	Root faults	SI	Root faults	SI	Root faults	SI
$M_1$	0.0625	$M_3$	0.0000	$M_5$	0.1875	$T_7$	0.1875
$M_2$	0.0625	$M_4$	0.0000	$T_6$	0.1875	$S_3$	0.1875

From table 6,  $M_5, T_6, T_7$  and  $S_3$  are more important than the other faults. There are some recommendations for the designers to improve the reliability of the hinges. Table 7 shows the root faults and the improvement measures of the hinges.

**Table 7.** Root faults and improvement measures (hinge)

Root faults	Contents	Improvement measures
$M_5$	The fault of the seal	Use new lubricant with suitable viscosity and less volatile.
$T_6$	The insufficient torque of the locking spring	Designers can change the material to get a larger stiffness of torsion spring and change the preload to prevent the spring from being lack of energy.
$T_7$	The changeable temperature in space (harsh thermal environment)	Investigate the temperature in space precisely where the solar array works and sum the rules for hinge use; use new materials that are fit for the change of the temperature in space; the change of temperature and radiation in space may cause the damage of the solar array [21].As a result, designers must research the damage accumulation on the structure of the hinge on the basis of the space environment.
$S_3$	The high friction force	The curve on the inner hinge with a groove can be optimized, and the further research can be focused on the mechanism of friction in space environment. Many researchers reported one new kind of hinge that is made of one certain tape spring [22]. The tape spring is installed between the two panels, simple but with high reliability.

### 5. Conclusions

The solar array is an important device which influences the quality of in-orbit operation of the spacecraft and even the launches. The FTA model of the mechanical system of solar array is established on the basis of the working process of the system. From the analysis of the FTA model,

it can be concluded that thermal deformation of the solar panel, deformation of the locking hole, deadlocking in hinges and particles in space are the critical causes of the faults. Consequently, the performance of the solar array will be more stable with deeper researches of these faults and the anti-fault design methods. Faults caused by damage accumulation which cannot be easily found but may result in the failure of the system should be noted especially.

According to the results of the reliability analysis of the solar array, the hinges are the key subsystem of the solar array, faults of which occupy 40% of all the faults in the solar array. So it is essential to analyze the reliability of the hinges. The analysis result of the hinges based on FTA shows that the fault of the seal, insufficient torque of the locking spring, changeable temperature in space and large friction force are the fatal causes, which own the SI of 0.1875. Damage accumulation caused by the harsh space environment is considered in the analysis. The improvement should be focused on the mechanical structures and the thermal environment of the space.

### Acknowledgments

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