FMEA as a Design Improvement Tool of protoMIRAX Attitude Control Subsystem

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Abstract

This paper aims to report the contribution of a Failure Mode and Effect Analysis (FMEA) on the Attitude Control Subsystem (ACS) design for the scientific experiment protoMIRAX. As a design verification tool, FMEA allowed to identify the critical points and potential product failures, to assess their effects and to suggest failure compensating measures. The recommendations raised at the end of analysis provided guidelines to subsystem functional/operational improvements.

1. Introduction

This paper addresses the problem of improving the design of an attitude control subsystem (ACS) for a stratospheric balloon payload. The technique used was the Failure Mode and Effect Analysis (FMEA).

The FMEA is an engineering technique used to define, identify, and eliminate known and/or potential failures, problems, errors, and so on from the system, design, process and/or service before they reach the customer [1]. One of the main requirements for a FMEA is to identify the system critical points. It is performed to assess the effects of the identified failures in order to define mitigation actions, starting with the highest-priority ones related to failures having the most critical consequences [2].

The FMEA allows the determination of preventive actions, as they can support trade-off decisions in terms of reliability, safety, as well as supports the definition of requirements of the product related to features such as redundancy, constraints, and operations to be performed in order to prevent injury or loss of mission.

In the aerospace domain, a satellite attitude control system stabilizes the spacecraft and orients it in desired directions during the mission, despite the external disturbance torques acting on it [3]. According to Tafazoli [4], who studied 156 cases of on-orbit spacecraft failures occurring from 1980 to 2005, the subsystem that suffered more failures was the Attitude and Orbit Control System (AOCS), with 32% of failures among all the spacecraft subsystems. Particularly in the protoMIRAX project, used as a case study in this paper (described in Section 2), a failure in the ACS can cause a loss of mission. These facts demand the use of some systematic technique to improve the design of the ACS. FMEA is probably the most widely used and most effective design reliability analysis method [5].

The FMEA application in the protoMIRAX ACS aimed the following benefits: improving the ACS design as well as the product and mission; identifying critical features of the ACS; support the definition of corrective actions; and produce historical documentation that can be useful as reference in future applications.

This work was executed by the following participants: COMPSIS Company responsible for developing the protoMIRAX system ACS; INPE (National Institute for Space Research) Space and Atmospheric Sciences (CEA); the Laboratory of Concurrent Engineering Systems (LSIS) from Laboratory of Integration and Testing (LIT/INPE).

The paper is organized as follows. Section 2 describes the protoMIRAX scientific experiment, used as a case study of the work, while Section 3 describes the attitude control system of the protoMIRAX. Section 4 presents the application of FMEA to the ACS. The results obtained from the FMEA are described in Section 5, and finally Section 6 concludes the paper.

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2. The protoMIRAX scientific experiment

The goal of protoMIRAX Project is the development and operation of a scientific experiment on a stratospheric balloon around 42Km altitude. The objective of this experiment is to collect scientific data using images, measurements of X-ray flow, power spectrum curves and variability of cosmic sources in space. Figure 1 illustrates the protoMIRAX space segment elements.

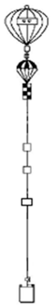

Figure 1. protoMIRAX elements schematic

The experiment is a test platform for MIRAX (a satellite scientific payload under development by INPE) that will deploy low earth orbiting X-ray telescopes to continuously monitor the central region of the Galactic plane.

The protoMIRAX is a Brazilian project with FINEP financial support executed by INPE High Energy Astrophysics international group, in partnership with COMPSIS, an aerospace Brazilian Company.

The protoMIRAX Project promotes the development of national space technology for attitude control, telemetry, tracking and command systems, and embedded software onboard balloons and satellite vehicles. Moreover, the development of these technologies will contribute to improve the validation and verification processes currently used by CEA/INPE.

3. The protoMIRAX ACS

In the ProtoMIRAX scientific experiment, the attitude control subsystem (ACS) plays an important role for the mission success. It is responsible for pointing the X-ray camera and tracking the targets of interest.

Figure 2 shows a schematic of the protoMIRAX gondola with a highlight to the ACS functions of azimuth and elevation control axes.

The ACS architecture is divided into three element blocks: controller, sensors and actuators.

The controller block is composed of the following elements: on-board computer and signal conditioning module. The controller is built around a modular PC-104 platform that executes the controller functions, provides the interfaces with sensors and actuators of the control system, and the interfaces with the onboard management subsystem.

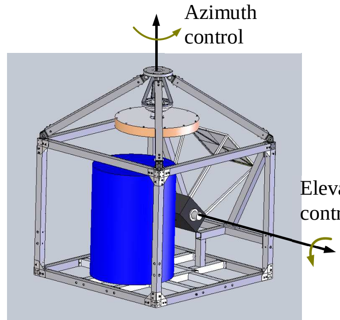

Figure 2. protoMIRAX gondola schematic

The sensors block is comprised of magnetic compass, star sensors, sun sensors, accelerometers, GPS unit and temperature sensors.

The actuators block includes the decoupling and desaturation mechanism, the X-ray camera elevation mechanism and the reaction wheel.

The ACS performs the following functions: (i) protoMIRAX gondola azimuth control; (ii) elevation control of the X-ray camera; and (iii) attitude control management. Each one of these functions encompasses sub functions detailed during the execution of the FMEA activities.

4. Application of FMEA to ACS

The use of FMEA is part of the Systems Engineering practices conceived in the context of LSIS/LIT. The process was conducted by a LSIS/LIT facilitator at the product level in a functional FMEA approach. It was entirely based on ECSS-Q-ST-30-02C [2].

The process adopted for the implementation of FMEA comprised the following sequence:

i) Production of knowledge from existing information;
ii) Initial population of the FMEA spreadsheet;
iii) Selection of the elements to be detailed;
iv) Completion of data for selected elements;
v) Issue of final report and presentation to the stakeholders.

In the **production of knowledge** phase (i) a set of documents from COMPSIS containing all the information about the subsystem was used as reference. Other existing documents ([6], [7], [8] and [9]) describing the protoMIRAX mission and subsystem were studied as well as a tree with thought-oriented product assembly and a functional tree, both developed in a previous work by LSIS. An interface matrix, populated by the ACS developers, to show the

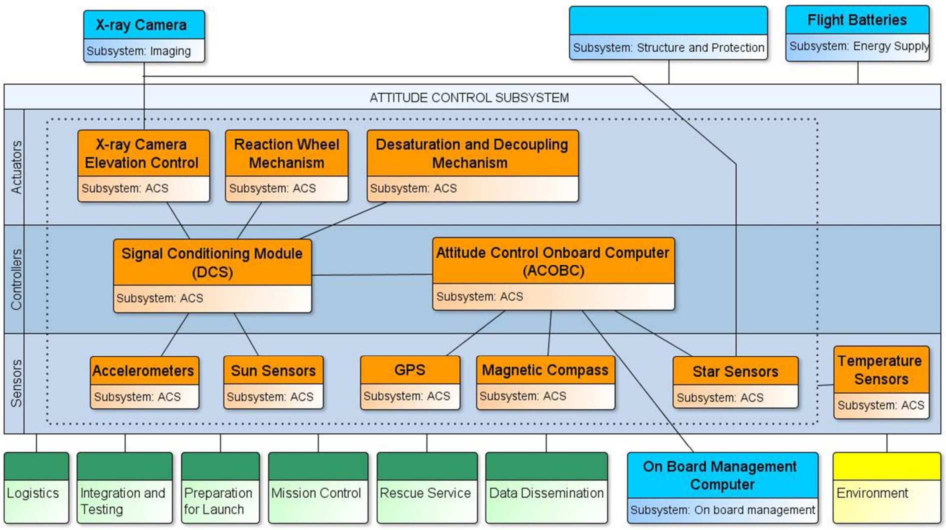

Figure 3. ACS context and interfaces

relationship between the elements in the context of physical contact, energy transfer, information exchange or material exchange was constructed thereon.

All this information was used to provide an initial understanding of the subsystem to be analyzed, mainly by the facilitator who could conduct the process accordingly. As result a context diagram (Figure 3) was created.

For the **Initial population of the FMEA spreadsheet** (ii) data collected in the previous step was used, identifying the elements and functions initially separately. Following, functions have been allocated to each element.

A sequence of meetings with the ACS development team took place in order to confirm the correctness of the existing FMEA table information, as well as to fulfill each of the remaining element functions. Then, the failure modes for each function and their possible causes were derived performing a cognitive exercise that consists of encouraging the meeting participants to structure the problem with the use of a facilitated brainstorming technique. This technique consists of providing initial data to the participants such that they could develop better projection of ideas, encouraging debate and consensus.

In the **selection of the elements to be detailed** (iii), the degree of severity was set for each element followed by a dedicated suffix, as suggested in the standard [2]. The degree of severity is related to the consequences of the failure mode under consideration. It can vary on a scale from 1 to 4, where: 1 is catastrophic, 2 is critical, 3 is major, and 4 is minor or negligible. The dedicated suffix can assume: SP to single point of failure; R for redundancy; and SH to indicate a security/health risk. The severity was defined for the selection of elements of which the detailed analysis should be performed, since a failure on these elements could lead to a hazardous subsystem or mission situation.

In the **Completion of data for selected elements** (iv), the elements selected in the previous step were better detailed with the identification of the mission phase and operational mode where failures might occur. Then, the local and global effects of the failure modes associated to the mission phase and operational mode were identified. In addition, possible methods of failure detection or observable symptoms, as well as compensation measures and recommendations were listed.

In the **Issue of final report** (v): following the information acquired from the analysis and the process of filling out the FMEA worksheet through meetings with the ACS subsystem developers , there was issued a report with the results summarized in the next section. There was also held a results presentation meeting to the stakeholders.

5. Results

The graph in Figure 4 shows the relative distribution of failure causes and failure modes derived for each element.

A single failure mode can be caused by many failure causes. Some of the failure causes are common to all elements. Thus, the total number of distinct failure causes identified for the ACS is smaller than the values shown in the figure.

Eight out of the eleven under study ACS elements were selected for deep analysis due to their severity, as they obtained one of the following severity classification: 1 - catastrophic; 2 - critical; and 3 with a single point of failure (SP) - major.

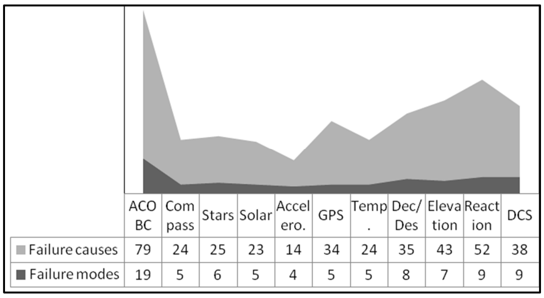

Figure 4. ACS elements failure modes and causes

Despite having a low associated failure severity, the star sensor was studied in detail as well - the stakeholders were interested in obtaining a better understanding of this element. Table 1 lists these elements along with their identification and severity ranking.

Table 1. ACS elements analyzed

ID	Item/block	Severity
CA1	Attitude Control Onboard Computer (ACOBC) / Controller	2SP
CA2	Magnetic Compass Set / Sensors	2R
CA3	Star Sensors (SEA) / Sensors	4SP
CA6	GPS Unit / Sensors	3SP
CA8	Desaturation and Decoupling Mechanism / Actuators	2SP
CA9	X-ray Camera Elevation Control Motor / Actuators	2SP
CA10	Reaction Wheel Mechanism/ Actuators	2SP
CA11	Signal Conditioning Module	2SP

Three elements from this table were fully analyzed. From the information obtained with the analysis methods to detect possible failures were identified: 23 to ACOBC, 10 to decoupling and desaturation mechanism and 13 to the star sensor.

Recommendations to avoid the failures were raised for those elements: 49 to ACOBC, 7 to decoupling and desaturation mechanism and 7 to the star sensor.

There was raised the attention to some causes like the environmental constraints (-55°C to +60°C) indicating the need for further thermal analysis; low pressure (near vacuum) and structural misalignments due to thermal effects on star and sun sensors – need for a structural analysis combined with thermal analysis. Desaturation mechanism bearings lubrication, star sensors thermal stress on its optical parts and harm on the gondola after ground impact were potential failure causes that have driven the attention to design improvement recommendations, to name a few.

6. Conclusions

This paper described the application of FMEA, an engineering technique used to improve a system design (among other benefits), for a stratospheric balloon payload attitude control subsystem (ACS).

The process promoted a better understanding of the subsystem behavior by both the facilitator of the process and the developers themselves. They developed a systemic view of ACS in the design process.

This knowledge showed areas for improvement in the system and points that deserve more attention and also met the FMEA major requirement of identifying the critical points. It also raised observable symptoms and compensation measures in the event of failures.

The compensation measures anticipate actions to be taken to ensure the subsystem performance for mission success.

Another achievement of the FMEA application was the recommendations for design improvements. Some of these recommendations had already driven the developers along the meetings to improve parts of the ACS design or to suggest another approach for its implementation.

Therefore, the application of FMEA to the attitude control subsystem was a valuable effort to contribute as a design decision making tool.

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