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SPACECRAFT FAILURE ANALYSIS FROM THE PERSPECTIVE OF DESIGN DECISION-MAKING

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ABSTRACT

Space mission-related projects are demanding and risky undertakings because of their complexity and cost. Many missions have failed over the years due to anomalies in either the launch vehicle or the spacecraft. Projects of such magnitude with undetected flaws due to ineffective process controls account for huge losses. Such failures continue to occur despite the studies on systems engineering process deficiencies and the state-of-the-art systems engineering practices in place. To further explore the reasons behind majority of the failures, we analyzed the failure data of space missions that happened over the last decade. Based on that information, we studied the launch-related failure events from a design decision-making perspective by employing failure event chain-based framework and identified some dominant cognitive biases that might have impacted the overall system performance leading to unintended catastrophes. The results of the study are presented in this paper.

1 Introduction

Systems engineering encompasses both technical and project-management processes, and deficiencies in either or both of them can lead to serious consequences, especially in the case of complex, large-scale projects viz., space missions. Each space mission is a challenging project to undertake which involves numerous complex systems that require high attention to detail, thin design margins followed by thorough testing and inspection procedures. Many missions have failed over the years due to anomalies in either the launch vehicle or the spacecraft. Such (failed) missions with undetected flaws, even after rigorous testing and quality control, account for losses in the order of billions of dollars [1]. Understanding the reasons of failure not only benefits the satellite customers but also the tax-payers.

In the past, some studies have shown the statistics of spacecraft failures and analyzed the subsystem-wise failures contribution. Hecht and Fiorentino [2] classified the failure causes into seven categories: Design, Environment, Parts, Quality, Operation, other known and unknown factors, and presented historical failure trends according to the causes. Similar studies along with subsystem-wise failure statistics are presented in [3,4]. Several other studies [5, 6, 7] analyzed space mission failures from a Systems Engineering (SE) standpoint and attributed the failure causes to several lapses in the traditional systems engineering process.

Sorenson and Marais [8] studied project failures across various industries, analyzed the causes by framing them in a "actor-action-object" structure. Johnson [9] discusses the role of organizational culture on mission outcomes, and highlights the importance of human-decision making and the role of social and psychological factors in failures. Causal analysis of failure events include categorizing the failure causes into three classes: proximate causes, root causes, and contributing factors. Johnson [9] points out that "the failure effects and proximate causes are technical, but the root causes and contributing factors are social or psychological", and emphasizes the importance of performing research to better understand how humans make mistakes and the circumstances that increase our 'natural error rates.'

It is well established that biases and heuristics play an important role in decision-making under uncertainty [10]. Further studies have suggested that humans are susceptible to error-prone judgments (and decisions) while undertaking tasks with hard deadlines and tight schedules [11, 12]. In this paper, we analyze some of the failures from the perspective of design decision-making. First, we observe the major failure contributors and categorize them by analyzing mission failures (launch and on-orbit satellite) that happened over the past decade (2009-2019). Based on this information, we study ten mission failures in the major failure category for which the post-failure investigation reports are available online. By breaking-down each failure event into its proximate and root cause(s), we infer the contributing factors from a human decision-making perspective, taking cues from some of the keywords used to describe cognitive biases and heuristics. Finally, we present some common cognitive biases that are observed from the contributing factors.

This paper is organized as follows. In Section 2, we present some statistics about space mission failures that happened over the last decade. In Section 3, we present the framework employed to analyze the failure causes. In Section 4, we discuss about some common cognitive biases identified among the failures, followed by results and conclusions in Section 5.

2 Space Mission Failures

To analyze the statistics of space mission failures, we gathered publicly available data about the failure events of space missions that happened over the last decade (2009-2019, from [13, 14, 15, 16, 17]). The data includes a total of 91 commercial, experimental and scientific-purpose launches by several countries. For the purpose of this study, we broadly classify failures into two categories: (i) Launch vehicle-related failures, and (ii) Payload-related failures. Launch vehicle-related failures are further categorized into payload-fairing separation failures, other failures which includes partial failures, and failures due to other sub-system anomalies. Launches which resulted in a loss of performance without a significant mission loss are included under partial failures. Such cases attained mission success despite some launch issues. Payload failures are categorized into on-orbit and partial failures after separating the payloads lost during the launch phases (and before reaching the intended orbits).

Figure 1 highlights the launch vehicle-related failures statistics: 38 missions out of a total 91 have successful launches, and the remaining 53 missions have launch vehicle related anomalies. Out of the 53 launch anomalies, 8 missions failed due to fairing separation issues, and 8 missions achieved partial success. A total of 37 missions failed at the launch stage due to other subsystem related issues. Figure 2 depicts the failure statistics of 100 payloads that are aboard the 91 missions: 44 payloads are lost during the launch and separation stages (before reaching the orbit), 32 payloads failed while being on-orbit and 17 suffered partial failures.

All the failure cases are further analyzed and the category-

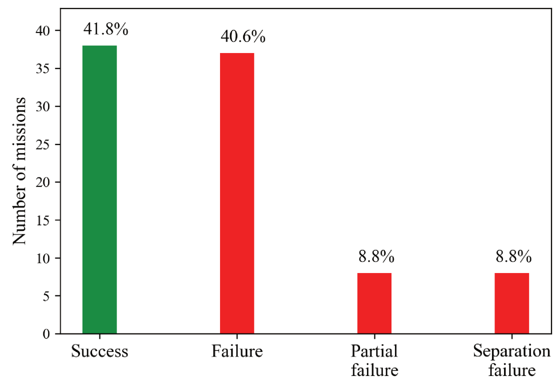

FIGURE 1. Launch vehicle related failure statistics in the last decade (2009 to 2019)

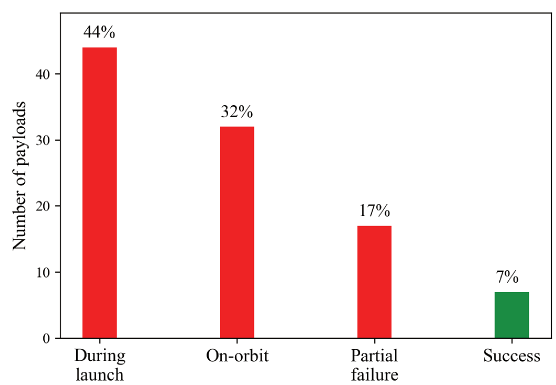

FIGURE 2. Payload failure statistics in the last decade (2009 to 2019)

wise statistics are shown in Figure 3. The "Design" category, which accounts for 63% of all failures, covers all the cases that failed due to design-related errors in power, propulsion, engine, structures and thermal subsystems. Very few cases with anomalies in Communications, AD&C (Attitude Determination and Control) subsystems are reported along-side some missions with programming errors. As apparent from the failure data, majority of the projects suffered from design-related issues. Such design-related failure events are further studied to understand the human decision-making aspects behind some of the failure-causing design decisions.

3 Framework

Previous studies on mission failures have identified problems and patterns of causation in accidents [8]. While some studies [1,2,3,4] presented the failure statistics, others [5,6] analyzed the problems from a systems engineering point-of-view and to the best of the authors' knowledge, none of the studies attempted

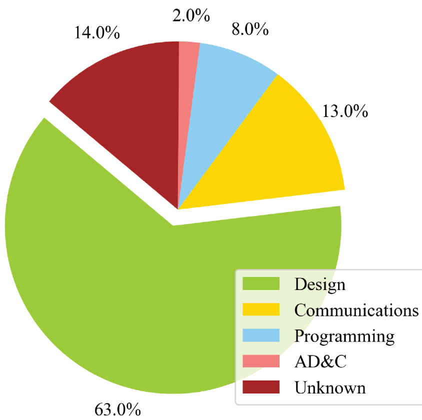

FIGURE 3. Break-down of space-mission failures (2009 to 2019)

to explore the failure events from a decision-making perspective. In this study, we present an approach to analyze the failures from a decision-making point of view by following the failure event chain-based framework, as depicted in [9].

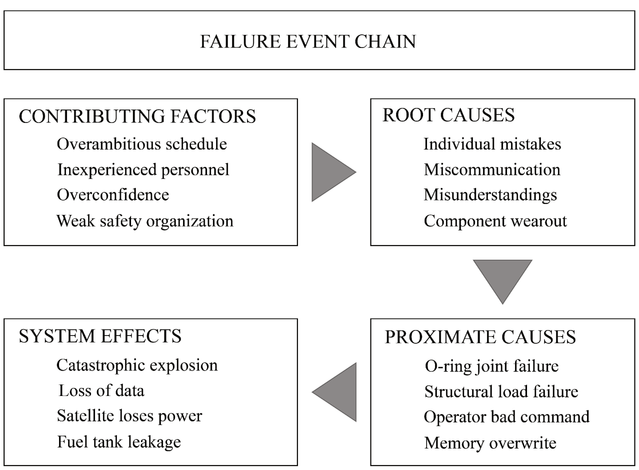

FIGURE 4. Failure event chain as depicted in [9]

According to Johnson [9], 'culture' is an ambiguous term "that covers a lot of ground, including patterns of human knowledge, beliefs, behaviors, and social forms." To understand such human-behavioral patterns behind the causes leading to technical failures, he presented a failure event chain (shown in Figure 4) with contributing factors as the starting point towards system failures. Based on this, we analyzed a set of ten missions that failed catastrophically due to design flaws for which the failure-investigation reports are publicly available online. These missions had undetected design flaws that resulted due to management overconfidence, poor quality control, unskilled labor, inadequate design margins, uncontrollable manufacturing process etc., and are briefly discussed in the following section.

4 Analysis of a set of failures

Acquiring detailed information on space mission failures is difficult, in general, and the organizations involved carry out investigations at their own discretion. From publicly available resources, we are able to extract failure-causation information of ten missions that took place over the last decade. These missions suffered catastrophic failures during the launch stages which destroyed the launch vehicles and the payloads well before orbital-insertion. Table 1 illustrates the failure events data of the ten missions along with their launch dates, gathered from the respective references mentioned against each mission. These references include publicly accessible websites with information from the respective mission investigation reports and publicly released mission investigation reports.

We studied each failure event in detail, to identify the proximate cause(s), root cause(s) and the contributing factor(s). According to [7, 9], a *proximate cause* is defined as "a factor that directly led to the failure", a *root cause* is "a systemic factor that caused or created conditions leading to the failure" and a *contributing factor* is "something that worked to allow or make more likely the failure." In the following section, we present the approach used to isolate the proximate, root causes, and contributing factors for the failure events of the ten missions considered here.

4.1 Analysis Approach

For each mission in Table 1, we studied the failure events, extracted the proximate and root causes, and construed the contributing factors based on the definitions given above. We demonstrate our approach using the Proton-M launch failure that happened on 02-July-2013 (S.No. 2 in Table 1). From the mission investigation report details as mentioned in [19], we extracted the following statements with information about the failure causes:

1. "Each of those sensors had an arrow that was supposed to point towards the top of the vehicle, however multiple sensors on the failed rocket were pointing downward instead. As a result, the flight control system was receiving wrong information about the position of the rocket and tried to correct it, causing the vehicle to swing wildly and, ultimately, crash."
2. "Trail led to a young technician responsible for the wrong assembly of the hardware."
3. "It appeared that no visual control of the faulty installation had been conducted, while electrical checks could not detect the problem since all circuits had been working correctly."

TABLE 1. Spacecraft launch failure events

S. No.	Launch date	Vehicle and Payload(s)	Failure event	Ref.
1	16-May-2015	Proton-M/Block DM-03 with MexSat-1	"Third stage steering engine failed due to intense vibrations caused by an increasing imbalance in the rotor inside the engines turbo-pump."	[18]
2	02-July-2013	Proton-M/Block DM-03 with three GLONASS satellites	"Critical angular velocity sensors installed upside down causing the vehicle to swing wildly and, ultimately, crash."	[19]
3	01-February-2013	Zenit-3SL/Block DM-SL with Intelsat-27	"Poor manufacturing processes and quality control lead to the failure of Zenit-3SL first stage hydraulic power supply unit."	[20]
4	08-December-2012	Proton-M/Briz-M with Yamal-402	"Launch anomaly was due to a combination of adverse conditions which affected the operation of the Briz M main engine during the start-up of the third burn."	[21]
5	06-August-2012	Proton-M/Briz-M with Telkom-3 and Ekspress-MD2	"Accident had been caused by a component of the pressurization system that was not manufactured to specifications."	[22]
6	24-August-2011	Soyuz-U with Progress M12-M	"A blocked duct due to a random production defect cut the fuel supply to the Soyuz-U's third-stage, causing its engine to shut down prematurely."	[23]
7	18-August-2011	Proton-M/Briz-M with Ekspress-AM4	"Inertial coordinate system on-board Briz-M upper stage failed due to a programming error between third and fourth firing and left the satellite in a wrong orbit."	[24]
8	04-March-2011	Taurus XL with Glory	"Payload fairing didn't separate as expected due to failed frangible joints."	[25]
9	05-December-2010	Proton-M/Block DM-03 with three GLONASS satellites	"Launch went wrong 10 minutes after take-off due to a miscalculation during the fueling of Block DM-03 upper stage, which received 1,582 kilograms of extra liquid oxygen above the maximum allowable limit."	[26]
10	24-February-2009	Taurus XL with OCO	"The OCO mission was lost in a launch failure when the payload fairing of the Taurus launch vehicle failed to separate during ascent."	[27]

4. "Along with a human error, the investigation commission identified deficiencies in the installation instructions and in the mechanical design of the hardware, which both contributed to the problem. For example, the mounting plate lacked an arrow which would match the direction of an arrow on the DUS unit."

The *proximate* and the *root causes* as inferred from the above statements are:

1. *Proximate cause*: "Flight control system was receiving wrong information about the position of the rocket" and an attempt to correct it caused the failure, ultimately.
2. *Root cause*: The flight control system was receiving incorrect information about the rocket's position because "multiple (angular velocity) sensors on the rocket were pointing downward" which were "supposed to point towards the top of the vehicle."

With the proximate and root causes being known, we finally extracted the following statements with information about the contributing factors:

1. "Trail led to a young technician responsible for the wrong assembly of the hardware."
2. "It appeared that no visual control of the faulty installation had been conducted, [...]"
3. "Along with a human error, the investigation commission identified deficiencies in the installation instructions and in the mechanical design of the hardware, which both contributed to the problem."

We followed a similar procedure to isolate the proximate and root causes of all the ten missions and the data is presented in Table 2.

TABLE 2. Failures root cause analysis

S. No.	Proximate cause(s)	Root cause(s)	Information about contributing factor(s)
1	Failure of third stage steering engine	Intense vibrations caused by an increasing imbalance in the rotor inside the engine's turbo-pump	Usage of cheap materials caused rotor material degradation at higher temperatures and hence, the imbalance
2	Flight control system was receiving wrong information about the position of the rocket	Critical angular velocity sensors installed upside down	Installation by an unskilled technician with improper installation instructions document followed by poor inspection
3	Hydraulic oil supplied to the main engine gimbal actuators not pressurized properly	Abnormal performance of the pump due to manufacturing issues	Factors associated with a pump manufacturing process that proved difficult to control
4	Main engine failure during the start-up of the third burn	Accumulation of large volume of oxidizer gas at the engine inlet, exceeding the main engine specifications	Inadequate thermal requirements definition followed by adverse thermal conditions at the lift-off
5	Main engine shut-down by flight control system	Blocked pressurization line in the auxiliary propellant tank	Component of the pressurization system that was not manufactured to specifications
6	Premature shut-down of third stage engine	A blocked duct caused reduced fuel consumption in the gas generator of the third stage	Usage of defective fuel duct
7	Upper stage inertial coordinate system failed between third and fourth firing	Inertial reference frame lost as the intermediate gimbal ring got stuck at the gimbal limit	Time allotted for the delta rotation was incorrectly entered in the flight program
8	Payload fairing of the launch vehicle failed to separate	Failed frangible joints due to 'not-so tightly controlled' manufacturing processes	Did not consider all flight environmental effects and the system performance margins were not updated accordingly
9	Launch fail due to extra mass of the propellant	Miscalculated the amount of fuel needed to be loaded into the rocket booster; exceeded the norm by 1-1.5 tons	Propellant filled-in according to old instructions and necessary pre-launch safety procedures were not carried out
10	Payload fairing of the launch vehicle failed to separate	Possible subsystem failures: Frangible Joints, Electrical and Pneumatic	Unable to determine a direct cause that lead to the fairing malfunction

4.2 Contributing factors

Based on the information presented in Table 2, we identify the social and/or psychological contributing factors that increased the likelihood of error propagation through different phases of systems engineering. For the example mission described in Section 4.1, the following two statements provide details of the possible contributing factors (shown as bold text):

1. "It appeared that **no visual control of the faulty installation had been conducted**, while electrical checks could not detect the problem since all circuits had been working correctly."
2. "Along with a human error, the investigation commission identified **deficiencies in the installation instructions and in the mechanical design of the hardware**, which both contributed to the problem."

Such anomalies, mishaps, and eventual failures are possible results of lapses in team and/or human decision-making and are studied further as described in the following section.

4.3 Engineering Decision-making and Cognitive biases

According to [28], systems engineering includes both management and technical processes that depend on good decision-making. Decisions are made throughout the life cycle of every system whenever alternative courses of action exist and every decision involves an analysis of the alternative options for eventual selection of a course of action. Decisions made early in the life cycle of a system, whose consequences are not clearly understood, can have enormous implications later in the life of a

TABLE 3. Contributing factors analysis

S. No.	Information about contributing factor(s)	Contributing factor(s)	Dominant Bias(es) and reasons
1	Usage of cheap materials caused rotor material degradation at higher temperatures and hence, the imbalance	Usage of cheap materials, ineffective quality control	1. Anchoring bias 2. Normalization of deviance (Optimism bias)
2	Installation by an unskilled technician with improper installation instructions document followed by poor inspection	Improper technical manuals, unskilled technician, ineffective quality control	1. Anchoring bias 2. Overconfidence (Optimism bias)
3	Factors associated with a pump manufacturing process that proved difficult to control	Uncontrollable manufacturing process, ambitious requirements	Normalization of deviance (Optimism bias)
4	Inadequate thermal requirements definition followed by adverse thermal conditions at the lift-off	Inadequate requirements definition, inadequate safety margin	1. Anchoring bias 2. Overconfidence (Optimism bias)
5	Component of the pressurization system that was not manufactured to specifications	Component manufacturing specifications not met, poor quality control	1. Anchoring bias 2. Normalization of deviance (Optimism bias)
6	Usage of defective fuel duct	Production line defect, poor quality control	Overconfidence (Optimism bias)
7	Time allotted for the delta rotation was incorrectly entered in the flight program	Programming error, lack of program checks	Overconfidence (Optimism bias)
8	Did not consider all flight environmental effects and the system performance margins were not updated accordingly	Poor manufacturing process control, system performance margins not updated	1. Overconfidence (Optimism bias) 2. Normalization of deviance (Optimism bias)
9	Propellant filled-in according to old instructions and necessary pre-launch safety procedures were not carried out	Pre-launch safety procedures not carried out, outdated operational documentation	1. Overconfidence (Optimism bias) 2. Normalization of deviance (Optimism bias)
10	Unable to determine a direct cause that lead to the fairing malfunction	Poor quality control and inspection processes	Overconfidence (Optimism bias)

system. Teams involved in designing, developing, testing, and validating complex space systems make numerous decisions over the course of a project.

Several subject matter experts (SMEs), engineers and technicians often exchange information based on these decisions within their teams, with other teams and managers, and with third parties (external contractors, service providers etc.). These decisions include, but are not limited to, choices about feasibility studies, requirements definition, component selection and design, testing, validation and operations covering launch, deployment and re-entry phases. Such decisions should be objective and completely unbiased in nature. But, it is well established that humans are prone to the biases that originate by being reliant on judgmental heuristics while making decisions under uncertainty [10]. Some common types of cognitive bias that are known to affect decisions include anchoring bias [10], optimism bias [29], confirmation bias [30] and outcome bias [31]. These biases are briefly explained below:

1. *Anchoring bias*: The tendency to get "anchored" to a particular piece of information that one may have acquired for the first-time, or, to an expected result, when making decisions.
2. *Optimism bias*: "The tendency to overestimate the likelihood of positive events, and underestimate the likelihood of negative events". This bias is caused due to 'Representativeness heuristic', leads to overconfidence in results and a phenomenon called 'Normalization of deviance' [32].
3. *Confirmation bias*: The tendency to seek or interpret an evidence in ways that are partial to existing beliefs, expectations, or a hypothesis in hand which leads to 'overconfidence' in one's actions.
4. *Outcome bias*: The tendency to support a decision with favorable outcome over a decision with unfavorable outcome instead of the quality of the decision itself.

With this information about cognitive biases being known, we studied the contributing factors further in-depth, to identify any potential biases that might have initiated the anomalies or errors that ultimately lead to the aforementioned failures. Following from Section 4.2, the contributing factors are analyzed (as described below) by identifying the probable reasons and attributing some possible biases to explain the deviant behavior of the agents (managers, engineers, technicians etc.) and/or that of the firms involved in the mission.

1. *Contributing factor*: Lack of visual control of installations
   Reasons: Overconfidence and anchored to previous quality control procedures
2. *Contributing factor*: Improper/outdated/ambiguous hardware design, installation instructions
   Reasons: Lack of knowledge, overconfidence and anchored to previous designs and installation manuals

Following a similar procedure for the other nine projects, we inferred the possible biases that would have affected the decisions of the concerned individuals. Table 3 lists the contributing factors and the biases for corresponding root causes of the ten missions under consideration. Some of the key results from this study are presented in the following section, along with recommendations for reducing the effects of cognitive biases in workspace.

5 Results and Conclusions

In this work, we set out to understand the decision-making lapses that triggered the failure events of some of the satellite launch vehicles. From Table 3, it is observed that *anchoring bias* and *optimism bias* are the dominant cognitive biases behind majority of the failure events. Decisions made with such biases can lead to unwarranted overconfidence and phenomena such as *Normalization of Deviance*, which is the tendency to accept risks as normal until a failure happens [32] in the absence of immediate failures. This work forms a basis in studying more complex individual and group decision making phenomena such as Groupthink, overconfidence and Normalization of Deviance.

So far, studies on failures are carried out from a Systems Engineering perspective and not from a human decision-making perspective. This work presents an approach to identify some dominating cognitive biases so that techniques to mitigate the biases them could be developed. Such cognitive biases come into effect when making decisions under uncertainty, which might be due to lack of adequate data, resources, etc. Educating and raising awareness about the negative impacts of cognitive biases on engineering decision-making among the project staff is an important starting point to mitigate their effects and eventual consequences.

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