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REQUIREMENTS FOR A FAILURE MODE TAXONOMY FOR USE IN CONCEPTUAL DESIGN

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Abstract

In this paper, we present the current state of a failure mode taxonomy, and discuss its potential to explore the failure mode space of aerospace applications. More fundamentally, we discuss what constitutes a good description of a failure that can be detected at the conceptual design stage. Elemental (physics-based) descriptions of failure modes are derived for several domains identified through analyses of historical accident and failure databases for NASA applications. The end product will offer a standard failure mode taxonomy that can be used in conjunction with a functional modeling approach to help detect potential operational failures early in conceptual design

Keywords: Failure mode taxonomy; Functional modeling-based failure analysis; Failure mode standardization; Failure detection.

1 Introduction

Though undesirable in all domains, failures are particularly unacceptable for NASA missions where safety becomes the top factor in determining the success of a mission. To deal with this reality, there is a current push towards including safety and risk assessment in the early stages of conceptual design. In our research, we propose a new approach by adapting the well-accepted functional modeling concepts used in conceptual design to risk and failure assessment in design. The main hypothesis of the research is that there is an inherent correlation between failure modes and the functionality of the components that make up a design. By starting with a form-independent description of the design, the approach introduces a means to explore possible failure modes early at the conceptual design stage.

The function-failure design method, developed by Tumer and Stone [1] relies on a knowledge base of observed failure modes for a given component set, as well as a knowledge base of the component functionality. To derive functionality, we rely on the functional taxonomy previously developed by Hirtz et al. [2]. To derive the failure modes, we seek to develop a comprehensive failure mode taxonomy, which is the focus of this paper. Each of these knowledge bases is represented as a two-dimensional matrix. Through simple matrix manipulations, failure modes can be related back to product function and similarities between function, component and failure mode can be exploited for conceptual design of new products and redesign of existing products [3-5].

For the above described method to be useful in conceptual design, we need a comprehensive failure mode taxonomy that designers can use to describe and analyze potential failures. In this paper, we report on our research findings related to the formulation of failure mode taxonomies. The first step of our research approach is to develop a failure mode taxonomy that describes the physical process of failure for mechanical, electrical and mechatronic product domains from engineering design literature. Our general approach is to test the failure mode taxonomy with empirical data, using a review of aerospace failure cases including rotorcraft and spacecraft components and subsystems. Through this process, we can then update the failure mode taxonomy and check its completeness by observing the gradient of new failure modes added vs. number of failure cases.

We have produced a preliminary failure mode taxonomy that provides coverage for failure cases seen in rotorcraft and are currently working with experts at NASA to understand spacecraft operational failures and add them to the taxonomy. This taxonomy adds to previously established mechanical failure modes listings, first proposed by Collins and Hagan [6] by incorporating newer material failure modes. Furthermore, for electrical and mechatronic domains, the taxonomy consolidates and extends previously isolated works in the area. We have access to multiple NASA and NTSB knowledge bases related to these domains that contain observed operational failure modes linked to component and function [3, 7]. The failure mode taxonomy developed in this research will be derived from a combination of such resources. The set of failure modes derived from these knowledge bases provide input for a prototype design tool for consideration of failure modes in the conceptual design phase.

2 Background and Motivation

2.1 Failure Modes and Effects Analysis (FMEA)

FMEA is the standard failure analysis method used in design [8, 9]. A rigorously performed FMEA contains valuable information about the various components and assemblies of the product, which helps in the early detection of weaknesses in a product's design. The FMEA procedure is still considered by most organizations as laborious and costly both in terms of money and time. More often the efforts have had poor results due to poor reusability arising from the inconsistent descriptions of the functions of the components or systems and the failures they undergo. Wirth et al. [10] have identified two fundamental weaknesses in the conventional FMEA. These are: the lack of methodological guideline to conduct an FMEA, and, the employment of natural language in recording the FMEA related information. They have addressed the problem of natural language in the description of functions using system and function taxonomies derived from the set of verbs and operators or fluxes provided by Roth [11] and Pahl and Beitz [12]. But there continues to be a lack of consistency in the description of failure modes. An engineer might describe different occurrences of the same failure in different ways or the same description for two marginally different failures. This lack of consistency makes the classification of failures that might manifest a particular set of symptoms difficult to identify, which otherwise would be a great source of help in diagnostic analysis [13, 14]. Thus standardization of both the function vocabulary and failure mode vocabulary is desired in this work.

2.2 Classification of Failure Types

The increasing importance of reliability metrics is fueling the advancement of reliability prediction methods, especially those used in new designs. Researchers have developed methods to classify and provide failure mode data to designers at an early stage. Peecht and Dasgupta [15] discuss the application of the physics of failure approach to reliable product development. In this approach the designer specifies the design requirements based on customer requirement and supplier capability and also identifies the use environment. Next, stress analysis, along with the knowledge of stress response of the design materials, is used in identifying failure sites, failure modes, and failure mechanisms. Once the potential failure modes are analyzed, a failure mechanism model is obtained which enables a reliability assessment to be conducted on the product.

Thornton [16] classifies failures into three categories: Safety, Functional and Ancillary. Within these categories, failures are further classified into five general areas as design deficiencies, construction deficiencies, material deficiencies, administrative deficiencies and maintenance deficiencies. The paper further states that as much as 52% of the failures is due to design deficiencies, 25% due to construction, and 18% due to materials deficiencies.

Svalbonas [17] classifies failure into five general groups as design, material selection, material imperfection, material fabrication and service environment. Failures resulting from design deficiencies are usually associated with poor structural design aspects. The design phase is divided into five stages: 1) setting design specifications, 2) providing design analysis, 3) providing proper fabrication and inspection, 4) setting required quality assurance procedure and 5) providing proper purchase specification. An error in any of the above five stages is almost certain to introduce a failure mode into the product.

In this paper we begin with the failure modes categorization scheme utilized by Collins [18]. Collins postulated that all failure modes could be classified based on three characteristics: 1) manifestation of failure, 2) failure inducing agent and 3) location of failure. By selecting appropriate classification from the three categories mentioned above Collins describes 23 commonly occurring failure modes.

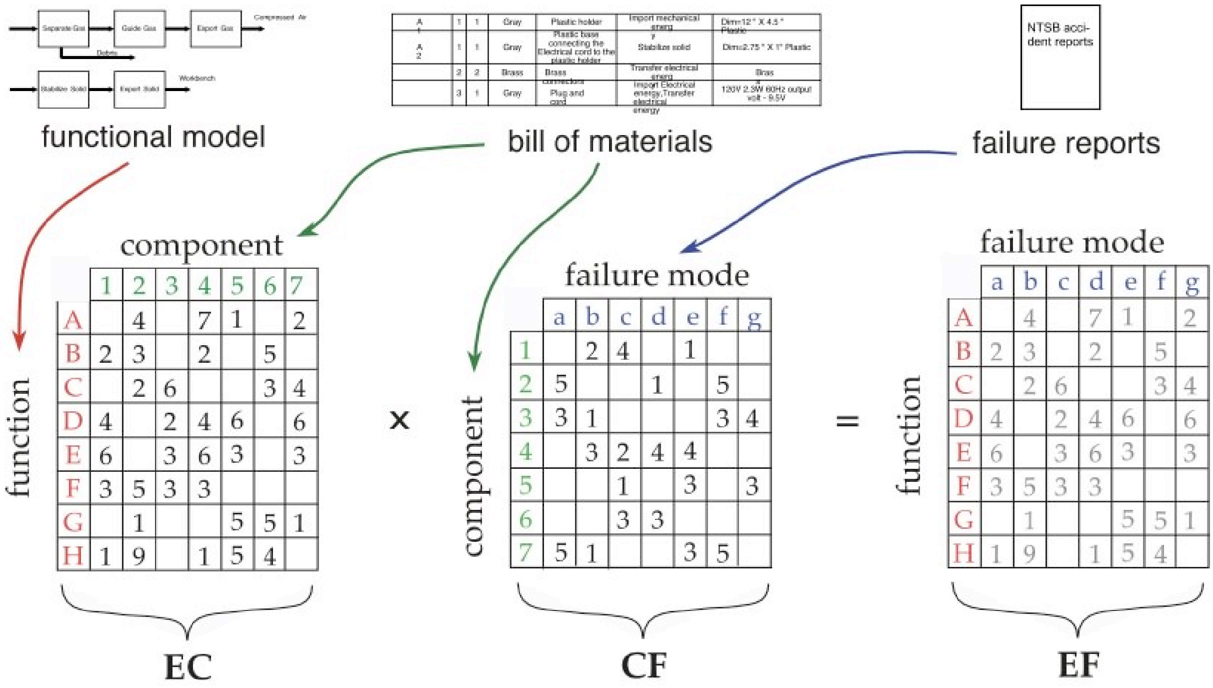
2.3 Exploring the Failure Space with the Function-Failure Design Method

The concept of applying matrix techniques to FMEA traces its origins back to the works of Collins [6] and Barbour [19]. Collins et al. [6, 18] are among the first to introduce the matrix approach to failure modes data recording. They devised a three dimensional matrix in which the axes represent the failure modes, elemental mechanical functions and corrective actions. Each failed part was classified by these attributes. The resulting Failure-Experience matrix forms a sound basis for cataloging failure data and as a potential engineering design tool. Its effectiveness as a design tool lies in its ability to accept real data and to generalize and normalize the data, which can then be used for a specific application. Goddard and Dussault [20] developed the Automated Advanced Matrix FMEA, which was a refined extension of Barbour's work, mainly serving as a logistics tool. The matrix was formed with the columns comprising of outputs of the assembly under analysis, test points of analysis, comments, remarks and references and the rows comprising of inputs to the assembly being analyzed with appropriate failure modes for the inputs and the parts contained in the assembly being analyzed with their failure modes. Henning and Paasch [21] also adopt a matrix-based approach to diagnose potential failure cases in proposed designs.

In our work, we formulate the function-failure design method, which involves the formation of a function-failure matrix that can be used as a knowledge base to identify and analyze potential failures for new designs and redesign. The overall procedure to create the knowledge base is outlined in Figure 1. The function-component matrix is composed of columns of components (obtained from the bill of materials) and rows of functions (obtained from the bill of materials and the functional model). The component-failure matrix is composed of rows of components and columns of failure modes. The function-failure matrix is obtained from the matrix multiplication of the two matrices:

$$\mathbf{EF} = \mathbf{EC} \times \mathbf{CF}. \tag{1}$$

Details of the theory and various applications of this work are presented in prior work and will not be described here in detail [1, 4, 5, 22]. The failure mode taxonomy discussed in the current paper is an essential requirement of the function-failure design methodology, used to describe and characterize the observed failure modes in a standardized way.



	1	2	3	4	5	6	7
A		4		7	1		2
B	2	3		2		5	
C		2	6			3	4
D	4		2	4	6		6
E	6		3	6	3		3
F	3	5	3	3			
G		1			5	5	1
H	1	9		1	5	4	

	a	b	c	d	e	f	g
1		2	4		1		
2	5			1		5	
3	3	1				3	4
4		3	2	4	4		
5			1		3		3
6			3	3			
7	5	1			3	5	

	a	b	c	d	e	f	g
A		4		7	1		2
B	2	3		2		5	
C		2	6			3	4
D	4		2	4	6		6
E	6		3	6	3		3
F	3	5	3	3			
G		1			5	5	1
H	1	9		1	5	4	

Figure 1. Schematic of the Function-Failure Design Method.

3 Towards a Standardized Failure Mode Taxonomy

In our research, we have identified two critical stages of FMEA: 1) the identification of component/system functionality; and, 2) the identification of failure modes. One of the most limiting aspects of FMEA is the lack of a standardized vocabulary to describe functionality and failure modes accurately and without ambiguity [14]. In this work, we use the functional basis developed by Stone and Wood [23] and Hirtz et al. [2] to describe functionality. This taxonomy has been tested in various environments and has been shown to provide designers with a repeatable and reusable standardized vocabulary to successfully explore the design space. Details of the functional taxonomy have been presented in prior publications [1, 23] and will not be presented in this paper. Instead, the focus is on the development of an equivalently repeatable and reusable standardized failure mode taxonomy.

3.1 Requirements for an Elemental Failure Mode Taxonomy

We have hypothesized that the use of functional models will improve the ability to explore the failure space early in conceptual design, independent of form and specific solutions. To aid in the characterization of potential failure modes, we assert that the use of "elemental" failure modes that describe the actual physical process that takes place to cause the particular failure mode, is necessary. A physics-based description of the failure mode provides designers with a true understanding of the nature of what failed. In addition, because a physics-based description provides an understanding of the failure modes at their most "elemental" state, we assert that such a characterization will provide a standardized failure mode taxonomy. A standardized taxonomy is necessary to prevent ambiguity when describing failures that have occurred, hence providing designers with a repeatable and reusable vocabulary to work with. For example, a failure mode from an FMEA might indicate that a connector was "broken", when a designer might benefit better from a failure mode defined as "brittle fracture", indicating the way in which the part broke, and hence the types of requirements a solution should have, as well as the types of analyses it should undergo to prevent a similar failure from occurring. For example, a possible solution to avoid this failure mode might be to choose a material that is not brittle.

3.2 Approach

The Collins failure classification is used as a starting point in this research. This failure mode taxonomy was initially tested using a simple design example during the development of the initial approach [1] and developed further with historical failure cases using published NTSB rotorcraft accident reports [4, 5]. The failure mode taxonomy was then used to describe failures commonly encountered in household appliances to test applicability to the same domain that was used to test the functional basis [22]. The taxonomy was then analyzed with experts at JPL to determine the required extensions to cover failure modes characteristic of spacecraft design and space missions [3]. Specifically, operational failure reports from a Problem and Failure Reporting Database at JPL were analyzed to derive failures that have occurred during five missions [24].

Table 1. Failure mode taxonomy extension.

Primary Identifier	Secondary Identifier	Failure Mode
(Corrosion) Material deterioration due to chemical or electrochemical interaction with environment	Surface exposed to corrosive media	Direct chemical attack
	Electrochemical corrosion of two dissimilar metals that come in electrical contact	Galvanic corrosion
	Localized in crevices, cracks and joints where stagnant solution is trapped	Crevice corrosion
	Localized development of array of holes or pits	Pitting corrosion
	Grain boundaries of Cu, Cr, Ni, Al, Mg, Zn alloys corrode due to improper heat treated	Intergranular corrosion
	One element of solid alloy is removed	Selective leaching
	Presence of abrasive/ viscid material flow that erodes the material	Erosion corrosion
	Bubbles near pressure vessel walls collapse and cause particles to be expelled form the surface	Cavitation erosion
	Hydrogen blistering, embrittlement, or decarburization	Hydrogen damage
	Food ingestion and waste elimination of living organisms where waste products act as corrosive media	Biological corrosion
	Fluctuating load combined with corrosion action creates stress raisers which accelerate fatigue which in turn exposes new layer to corrosion	Corrosion fatigue
	Applied stresses on a part in a corrosive media	Stress corrosion
(Wear) Undesired change in dimension	Combined adhesive and abrasive wear with the presence of a corrosive medium	Corrosive wear
	High pressure at contact sites Plastic deformation Rupture of junction	Adhesive wear
	Particles removed by harder mating surface or by particles/debris entrapped between mating surfaces	Abrasive wear
	Cyclic shearing stress by rolling or sliding contact Manifests as pitting, cracking, scaling	Surface fatigue wear
	Repeated plastic deformation Severe impact induced	Deformation wear
	Elastic deformation Impact induded Failure occurs by nucleation or crack propagation	Impact wear
(Impact) Impact load of large magnitude	Separation into 2 or more parts	Impact fracture
	Plastic or elastic deformation	Impact deformation
	Mating parts Small lateral displacements Joints not intended to move	Impact fretting
(Fretting) Small amplitude fluctuating loads or deformations at joints not intended to move	Surface discontinuities and micro cracks caused by fretting that propagate under cyclic loads	Fretting fatigue
	Surface degradation	Fretting corrosion
	Change in dimensions	Fretting wear
(Creep) Plastic deformation	Stress and temperature influence Accumulated change in dimensions interfere with part performance	Creep
	Buckling due dimension change	Creep buckling
	Prestrained or prestressed part relaxes Possibly aggravated by high temperature	Thermal/stress relaxation
	Rupture (into two pieces) occurs due to stress-time-temperature conditions Steady-state creep growth period is short	Stress rupture

Table 1 (continued). Failure mode taxonomy extension.

Primary Identifier	**Secondary Identifier**	**Failure Mode**
(Thermal) Fluctuating thermal load	Fluctuating loads or deformations induced	Thermal fatigue
	Extreme temperature Elastic deformation	Temperature induced deformation
	Thermal gradients produce differential thermal strains lead to yielding or fracture	Thermal shock
(Galling & Seizure) Sliding surfaces	Combination of loads, sliding velocities, temperatures, lubricants produce surface destruction	Galling
	Two parts virtually welded together	Seizure
(Spalling) Particle spontaneously dislodged from surface		Spalling
(Radiation) Nuclear radiation	Loss of ductility	Radiation damage
(Buckling) High and/or point load geometric configuration	Deflection increases greatly for slight increases in load	Buckling
(Fatigue) Fluctuating loads or deformation	Sudden separation into two parts Magnitude of load such that **more** than 10,000 cycles required	High cycle fatigue
	Sudden separation into two parts Magnitude of load such that **less** than 10,000 cycles required	Low cycle fatigue
	Rolling surfaces in contact Pitting, cracking and spalling of contact surfaces	Surface fatigue
	Repetitive impact Failure occurs by nucleation or crack propagation	Impact fatigue
(Ductile deformation) Ductile materal	Imposed operational loads produces elastic deformation of part	Force induced elastic deformation
	Plastic deformation	Yielding
	Curved surfaces Local yielding of mating members Static force induced	Brinelling
(Rupture) Separate into two or more parts	Brittle material Elastic deformation exceeded Granular, multifaceted fracture surface	Brittle fracture
	Dull fibrous surface from propagation of internal voids Ductile material	Ductile rupture
(Electrical) Charge trapping and interface trap generation	Alters transistor characteristics, increased threshold voltage or substrate current, decreased transduction	Hot carrier effects
Electrical transients by nuclear radiation, electromagnetic pulses, radar, lightning, and switching transients	Shorts, opens Higher current in semiconductor junctions resulting in melt down	Electrical overstress
High passages of current/ current density mostly in aluminum and silicon	Form vacancies or voids in wires causing resistance or open circuits	Electromigration
Introduction of Na+	Changes in threshold voltages or conduction short between adjacent devices	Ionic contamination
Excessive electric field across gate oxide	Shorts between transistor gate and drain	Gate oxide breakdown
High voltages 100-200 kV discharged through circuit	Dielectric breakdown Junction short circuits Cracks between isolated regions	Electrostatic discharge

The analyses of these various domains and databases have pointed to a need to extend Collins' original set of mechanical failure modes to include domains more characteristic of highly-automated NASA applications. For example, electrical failure modes could not be addressed by the Collins taxonomy. Table 1 gives the current state of the failure mode taxonomy, which includes an extension to the mechanical failure modes (in terms of categorizing the failure modes), as well as a first attempt to represent electrical failure modes. This extended list of failure modes was used to analyze the historical failure modes from rotorcraft accidents, as well as an initial set of reports from the space mission operational failures. Though initially sufficient, it is clear that space missions require consideration of newer domains, not encountered in rotorcraft reports. In the following sections, we present additional failure modes characteristic of newer materials and components. The new failure modes encountered deal with components composed of plastics, elastomers (rubber), printed circuit board (PCB) and glue joints. Ongoing efforts include identification of software and human failure modes.

3.3 Failure Modes for Plastics

Plastics are one of the most frequently encountered materials in this work. The Collins classification does not accurately describe all the failures encountered by plastics. As the use of plastics is growing, we classify the failure modes of plastics based on the list created by Spoormaker [25]. This classification, shown in Table 2, along with the Collins classification can describe most of the failure modes of plastics. The failure modes in bold are the additional failure modes for plastics, while the other failure modes are a part of Collins classification.

Table 2. Failure mode identification for polymers using primary and secondary identifiers.

Failure mode	
Creep Stress Rupture	**Ageing**
Stress Relaxation	**UV-Degradation**
Wear	**Cracking**
Fatigue	

3.4 Failure Modes for Elastomers

Elastomer, or rubber, was another material whose failure modes is not adequately described by the Collins classification. The failure modes in Table 3 are prepared from the failure modes identified by Greene Tweed Co. [26]. The failure modes in bold indicate new failure modes that were not a part of the Collins classification.

Table 3. Failure mode identification aid for elastomers using primary and secondary identifiers.

Failure mode	
Compression Set	**Heat Cracking**
Wear / Abrasive Wear	**Installation Damage**
Direct Chemical Attack	**Extrusion**
Heat Hardening	**Pock Marks**

3.5 Failure Modes for PCBs

The Collins classification is essentially a classification of mechanical failures. It can describe limited electrical failures by identifying them with temperature-induced deformations, where an excess of current caused a temperature increase and ultimately lead to the malfunction of the component. Our initial list of electrical failure modes, shown in Table 1, is quite general at this point and remains an ongoing work. Here we describe only the failure modes experienced by Printed Circuit Boards that are frequently encountered in products like printers, VCR and other electronic devices. The classification is developed from the work of Vishwanadham and Singh [27]. Table 4 gives the failure modes for a printed circuit board. All the failure modes are new and have never been addressed in the Collins classification.

Table 4. Failure mode identification aid for printed circuit boards (PCB) using primary and secondary identifiers.

Failure mode		
Prepreg Defect	Copper Etch Shorts	Partially Drilled Holes
Measling	Copper Etch Opens	Epoxy Smear
Crazing	Mechanical Circuit Damage	Nailheading
Haloing	Handling Defects Of Plated Copper Surface	Inner Plane Delamination
Blistering	Particulate Contamination	Pth Copper Grain Structure
Delamination	Pits And Scratches	Pth Copper Plating Defects
Solder Mask Related Defects	Reduced Conductor Spacing	Pth Solderability
		Pink Ring

3.6 Failure Modes for Glue Joint

The failure of a glue joint by themselves may not be a matter of great concern but when combined with other factors the impact can be substantial. The following failure modes of a glue joint in Table 5 are from the list provided by Wengert [28].

Table 5. Failure mode identification aid for adhesive joints using primary and secondary identifiers.

Failure mode	
Starved Joint	Unanchored Joint
Pre-Cured Joint	Under-Cured Joint

4 Discussion and Closure

This paper presents the development of a preliminary set of elemental failure modes that explain the physical process in which a failure occurred. The goal of this research is to develop methods and taxonomies to aid designers in making informed decisions about the types of design solutions to avoid, and the types of specifications and analyses required to prevent a similar failure mode from occurring. The proposed taxonomy presents a physics-based explanation of potential failure modes. This “elemental” failure mode taxonomy is an essential component of the function-failure design methodology developed by the authors: the method relies on empirical failure and accident data from reports and databases to determine the types of failures that result in problems and mishaps, and correlates them with the specific functionality of the components and subsystems that failed. Historical failure and accident reports are analyzed using the proposed failure mode taxonomy to provide an exact and unambiguous description of what failed. A mapping of failure modes onto functional descriptions of components is used to derive a function-failure knowledge base, which can then be used for designers to make decisions based on similarities between designs and failures mechanisms [1, 5].

In this paper, an initial set of physics-based failure modes developed by Collins et al. [18] for mechanical failures was extended to cover the types of failures encountered in sources such as NTSB's rotorcraft accident reports and NASA's Problem and Failure Reporting databases [3, 7]. An initial set of electrical failure modes have been derived and added to the initial taxonomy. In addition, the failure modes taxonomy has been extended to include materials and components like elastomers, plastics, printed circuit boards and glue joints, providing an initial set of elemental failure modes characteristic of NASA missions. Other critical failures due to software and human errors are left for future work, due to the difficulty in mapping them to a physics-based taxonomy.

This research asserts that a physics-based description of failures is required in order to provide a standardized "elemental" vocabulary that designers can use to understand the true nature of a failure. Some of the questions that still need to be answered revolve around the degree of "specificity" required to describe failures to designers in a way that is really useful to designers. To determine the proposed taxonomy's utility, testing of the taxonomy is currently being planned with designers and reliability engineers at JPL's design testing centers. In addition, the initial set of failure modes presented in the paper is not the minimum set of modes that can be encountered in missions. Further literature review and empirical testing is underway to establish the validity, exactness, accuracy, and completeness of the set of failure modes presented in this paper. These four attributes are necessary to derive a "complete" set of elemental failure modes that can be used as a standardized vocabulary for failure analysis in conceptual design.

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