Scientific Scale of Reliability

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"If you watch a glacier from a distance, and see the big rocks fallings into the sea, and the way the ice moves, and so forth, it is not really essential to remember that it is made out of little hexagonal ice crystals. Yet if understood well enough the motion of the glacier is in fact a consequence of the character of the hexagonal ice crystals. But it takes quite a while to understand all the behaviour of the glacier (in fact nobody knows enough about ice yet, no matter how much they've studied crystal). However, the hope is that if we do understand the ice crystal we shall ultimately understand the glacier."

R. Feynman, “The Character of Physical Law”

Introduction

Reliability Theory, since it's beginnings in 1950s, has been based on mathematical theorems rather then on scientific theories. Massive attempts where made to further applications of the existing mathematical and statistical methods and analysis without attempts for understanding "failure mechanics". Then, in 1980s, practicing reliability engineers and analysts, who have neither ability nor need to understand the mathematics, turned to what they have had, which is enormous practical experience of the observed failure modes of existing systems. Thus, a large number of “practical reliability methods" have been developed and used, all of which were based on the failure mode, effect and criticality analysis, but still without understanding and addressing failure mechanics. Consequently, during the last 50 years the Reliability Theory made very little progress, a part from a few exceptions, in the direction of becoming the science, in terms of making accurate predictions that could be confirmed with practical observations. The reason is very simple; neither statistics, which does not study causes of statistical behaviour, nor engineers whose “applied methods” were focused on meeting contractual and legal requirements, were able to provide a fertile ground for the development of reliability.

To support the above statement the fundamental expression for reliability will be used. It is generally accepted that reliability is the probability that a system will operate without failure during a stated period of time, thus:

$$R_s(t) = P(TTF_s > t) = \int_t^{\infty} f_s(t)dt = 1 - F_s(t) = 1 - \int_0^t f_s(t)dt \qquad 1$$

where: $f_s(t)$ is the probability density function of the random variable known as the Time To Failure of a system, $R_s(t)$ is the system reliability function and $F_s(t)$ is the System Failure Function.

However, during last fifty years the western defence, aerospace, oil and other industries, for all reliability predictions, risk and safety assessments, conformances, contracting and similar activities, have been using the following expression for reliability function:

$$R_s(t) = P(TTF_s > t) = e^{-\lambda_s t} = e^{-\frac{t}{MTBF_s}} \quad 2$$

where: λ_s is the failure rate of a system, which represents the average number of failures per each hour of operation, and $MTBF_s$ is the Mean Time Between Failures of the system (λ_s=1/$MTBF_s$).

Both expressions for reliability function clearly demonstrate that the system reliability follows the laws of probability. However, the first allows the probability laws to be driven by physical processes and phenomena that take place in the system or result from the interaction of a system with natural and human environment, whereas the second one has predetermine law of probability, irrespective of types of future systems and their operational conditions, maintenance policies and support strategies. To make the distinction between these to approaches to reliability the former will be called the scientific approach and the latter the administrative approach.

Consequently, the main objective of this paper is to argue that the scientific approach to reliability is the only way forward for all members of the reliability community who wish to make accurate predictions that will be confirmed during the operational processes of the future systems. For that to happen scientific understanding of failure phenomena is required. Further more, this paper advocates that physical scale from 10^{-10} metre to 10^{+10} metre must be considered in order for failure mechanisms like, fatigue, single event upset, foreign object damage, thermal degradation, creep, shift of the central of gravity and many others, to be understood. Only then, accurate and meaningful reliability predictions become possible, which is imperative for the development of Risk-Based Technology and Physics-Of-Failure Methodologies and their successful applications.

The Concept of Functionability

The development of science started when people began to study phenomena not merely observing them. People developed instruments and learned to trust their readings, rather than to rely on their own perceptions. They recorded the results of their measurements in the form of numbers. Supplied with these numbers they began to seek relationships between them and to write down in the form of formulas. Then the formulas became the only things they came to trust when they began to predict things they could not physically experience.

However, people communicate with each other by means of words, not formulas. Hence, when they want to speak about new phenomena they have to invent concepts that correspond to them. Even though these concepts are often quite extraordinary, people become accustomed to them and learn to apply them correctly and even create images for themselves that they associate with the new concepts.

As classical Reliability Theory covers the operational process of the system to the occurrence of the failure events only, and neglects the type and depth of maintenance and support processes, the concept of functionability, as the ability of being functional, that includes the impact of those processes of failure mechanisms was created by Knezevic, [1]. Hence, functionability is an emergence property of a system generated by the complex and time dependent interactions of the following properties of a system:

- Functionality principles of a system (mechanical, electronic, etc.)

- Structure/construction of a system (dependencies and redundancies)
- Operational concepts and scenarios (continues, seasonal, one off)
- Maintenance rules (schedule inspections, replacement, texting and so forth)
- Logistics support (training, spares, facilities, tools, equipment, etc.)
- Environmental conditions (climate and weather)

From functionability point of view, at any instant of time a system can be in one of the following two states:

- Positive Functionability State, PFS, which is the state of being functional
- Negative Functionability State, NFS, which is the state of not being functional

The motion of the system through functionability states is governed by the occurrence of functionability events, which are classified as:

- Positive Functionability Events, PFE, which cause the transition from NFS to PFS
- Negative Functionability Events, NFE, which cause the transition from PFS to NFS

Consequently, the life of a system could be considered as the motion of system through functionability states in respect to time. The pattern generated by this motion forms the system functionability trajectory.

Physical Scale of Functionability

At the MIRCE Akademy a large number of functionability phenomena have been observed and analysed in order to understand the mechanisms, the frequencies and the consequences of their occurrences on the life of large number of systems in order to determine and formulate their relationships. Finally, their physical relationships have been captured and described through mathematical means that enable accurate predictions of the motion of functionability thought the life of a system to be made. This has given "birth" to Mirce Mechanics (see Appendix 1).

Full understanding of the mechanisms of the motion of functionability phenomena that drive the occurrence of functionability events is essential, as statistical methods used to analyse and quantify reliability do not study the causes of statistical behaviour. Consequently, the systematic studies are applied to understand phenomena that cause the occurrence of:

- **Positive Functionability Events**: such as: birth, servicing, lubrication, visual inspection, repair, replacement, final repair, examination, partial restoration, trouble shooting, storage, modification, transportation, sparing, cannibalisation, refurbishment, health monitoring, restoration, packaging, diagnostics and similar.

- **Negative Functionability Events**, such as: thermal ageing, actinic degradation, fatigue, pitting, acid reaction, bird strike, warping, abrasive wear, suncups formation on the blue ice runway, thermal buckling, photo-oxidation, production errors, strong wind, maintenance error, hail damage, lightening strike, hard landing, quality problems, sand storm and so forth;

For years, research studies, international conferences, summer schools and other events have been organised in order to understand just a physical scale at which functionability phenomena should be studied and understood. In order to understand the motion of functionability it is necessary to understand the mechanisms of the motion. That represented a real challenge. Answers to the questions "what is the real cause of say, fatigue, the wind direction change, suncups formation on the blue ice runway, faulty weld, bird strike, perished rubber, maintenance induced error, carburettor icing", to name just a few, have to be provided. Without accurate answers to those questions the prediction of their future occurrences is not possible, and without ability to predict the future, the use of the word science becomes inappropriate.

After a numerous discussions, studies and trials, it has been concluded that any serious studies in this direction, from Mirce Mechanics point of view, have to be based between the following two boundaries:

- the "bottom end" of the physical world, which is at the level of the atoms and molecules that exists in the region of 10^{-10} of a metre ;
- the "top end" of the physical world, which is at the level of the solar system that stretches in the physical scale around 10^{+10} of a metre.

This range is the minimum sufficient "physical scale" which enables scientific understanding of relationships between system operational processes and system operational events. In other words, this is the physical range within which, the system operational processes mentioned above (fatigue, the wind direction change, suncups formation on the blue ice runway, bird strike, perished rubber, carburettor icing) take place and as such they could be understood and predicted.

The Bottom End: Atomic System

As matter is composed of atoms, its property is a consequence of the manner in which the atomic elements are arranged. Electron density describes the distribution of the electronic charge throughout real space resulting from the attractive forces generated by nuclei. It is a measurable property that determines the appearance and form of matter. The theory developed to describe the behaviour of electrons, atoms and molecules differs radically from known Newtonian physics, which governs the motions of macroscopic bodies and the physical events of our everyday experiences. The new theory was named quantum mechanics and is able to account for all observable behaviour of matter. The proper formulation of quantum mechanics and its application to a specific problem requires a rather elaborate mathematical framework, as do proper statements and applications of Newtonian physics. Hence, principles of quantum mechanics and its basic concepts are used for the studies of the motion and relationship between atoms in molecules. Thus, the physical laws governing the behaviour of electrons and their arrangements, when bound to nuclei, to form atoms and molecules have been discovered, and termed the electronic structure of the atom or molecule. Furthermore, understanding of the relationship between the electronic structure of an atom and its physical properties enables understanding of the change of electronic structure during a chemical reaction, where only the number and arrangement of the electrons are changed while the nucleus remaining unaltered. Thus, the unchanging charge of the atomic nucleus is responsible for retaining the atom's chemical identity through any chemical reaction. Therefore, for the purpose of understanding the chemical properties and behaviour of atoms, the nucleus may be regarded as simply a point charge of constant magnitude for a given element, giving rise to a central field of force that binds the electrons to the atom. [2]

The Top End: Solar System

The Solar System may seem enormous, looking from the human perspective, but it is only a very small corner of the Universe. However, the entire solar system contains only eight planets that move in elliptic paths around the Sun. All of them are lit by the Sun and do not produce their own light. The Sun's group of planets, together with their moons and other bodies, such as comets and asteroids is called the Solar System. The distance between the Earth and the Sun is 150 million kilometres; hence the number for the top end of 10^{10}. Each second the Sun radiates $4.2x10^{9}$ kg of photons, out of which Earth receives only 1.85 kg, which keeps our planet green and warm. Owing to them rivers flow, winds blow, forest rustle and the human race flourish. However, two kilograms of photons is not that small quantity. From Einstein's formula $E=mc^2$ their energy is $1.7x10^{17}$ joules, which is 20000 times the power of the world's industry (about 10^{13} watts). About a half of that energy ($0.8x10^{17}$ watts) reaches the terrestrial surface, which is $5x10^{14}$ square metres, making the average power of the solar radiation at ground level is 160 watts/m^2. The 99.9 % of it is absorbed by the soil, and goes into the evaporation of water, causing winds, thunderstorms, and all that we loosely call weather. Thus, only 0.1 per cent of the radiant energy of the Sun (around 10^{14} watts) is captured by plants through photosynthesis of organic substances from carbon dioxide and water. It is this energy that supports all the living things on Earth, from bacteria to animals and human.

From system reliability point of view, the solar system is significant in the respect to the "making" of the weather, which is the day-to-day condition of the atmosphere. It is one of the main drivers of system reliability, as it is "responsible" for the

- temperature and pressure of the air,
- wind speeds and directions,
- moisture in the air, precipitated as rain, snow, hail, sleet, dew or frost.

All air contains moisture in the form of water vapour, which is water in gaseous form. As warm air can hold more water vapour than cold air, when it is cooled its capacity to hold water vapour decreases, and finally the air is completely saturated, having a relative humidity of 100 per cent, known as *dew point.* Further cooling beyond dew point leads to water vapour condensing around nuclei, such as specks of dust or salt, to form water droplets or, in cold air, minute ice crystals. Large quantities of condensed water vapour form clouds, by which water is continually conveyed from the oceans to the land, where it is released from the air as precipitation. This provides the land with the fresh water needed by animal and plant life. Finally, the water completes the cycle by returning to the oceans.

Generally speaking there are three main kinds of rain: c*onvectional,* which occurs, especially in the tropics, when hot air rises and water vapour condenses into towering, often anvil-topped cumulonimbus clouds (inside the turbulent clouds, the water droplets collide, fuse together and fall as raindrops); *cyclonic,* that takes place in depressions when warm air rises above wedges of cold air along cold and warm fronts and occlusions (in the middle latitudes, clouds contain super-cooled water droplets, which are still liquid although their temperature may be as low as -40°C and ice crystals. The ice crystals collide with super cooled droplets and grow in size. They then start to fall, melting near the surface to become raindrops or, if the air is cold, they then join together to form snowflakes, or even hail) and *orographic rain* is created when air rises over a mountain range

Precipitation is a feature of storms. The commonest storms are thunderstorms, about 45,000 of which break out every day somewhere in the world. Thunderstorms occur when strongly rising air currents cause cumulonimbus clouds to form. As temperatures within the clouds fall, the outer shells of super cooled water droplets freeze and acquire a positive electrical charge. However, when the core subsequently freezes, it has a negative charge. The core expands as it freezes and shatters the outer shell, tiny splinters of which waft upwards, giving the top of the cloud a positive charge. The heavier cores remain lower down, building up a large negative charge. The air between the cloud and ground normally acts as an electrical insulator, but, when the charge on the cloud becomes great enough, the insulation breaks down and lightning occurs. Along the lightning's path, heat causes a violent expansion of the air, and the resultant compression wave is heard as thunder. Other storms include large, rotating hurricanes, also called tropical cyclones. They cause much damage. Especially because strong winds hurl high waves onto the shore, causing flooding. Tornadoes are smaller, measuring about 500 metres across. Wind speeds in these rotating, funnel-like columns of air may reach 400 mph (650 km/h).

The weather changes from one day to the next and is evident as variations in temperature, precipitation, wind and clouds. Examination of the weather over many years produces a pattern, which repeated over many years, constitutes the climate of a particular region. Obviously, different parts of the Earth have different climates. In equatorial region, the weather is always warm and usually wet. Deserts are dry, and Polar Regions cold. Hence, climate is the typical or average weather of a place based on records covering a period of years. The word climate comes from the Greek word *klima*, which means slope. The Greeks believed that the Earth 'sloped' from the Mediterranean southwards to the hot equatorial zone and northwards to the cold polar region. The different climate regions result partly from the Sun, whose radiation is stronger at the tropics than anywhere else, and partly from the way the atmosphere, and oceans, transfer the Sun energy away from the equator. If the Earth had no atmosphere or oceans, it could have no climates. The way in which the air and water produce climates is very complex and not yet fully understood.

An Example: Impact of Cosmic Rays on Avionics Reliability

In order to illustrate the necessity for the physical scale of studies of reliability phenomena proposed in this paper to be from 10^{-10} to 10^{+10} of a metre, the impact of cosmic rays on reliability of avionics will be presented here. It has been concern for avionics, since the late 1980's when the primary radiation phenomenon, which had previously been observed in orbiting satellites only, also began to appear in aircraft electronic systems. The interaction of this radiation with avionics can result in occurrence of Single Event Effect, SEE, which can be manifested as a transient 'soft error' effect such as a bit flip in memory or a voltage transient in logic. Alternatively, a 'hard error' can be induced resulting in permanent damage such as the burn out of a transistor. Due to the rapid advances in electronics technology and the unrelenting demand for increased avionics functionality in the competitive commercial aircraft industry, the complexity of avionics systems has risen exponentially. If device memory cells used for flight safety or mission critical functions are affected the concern is that the loss of key system functionality due to corrupted data could cause a flight safety or mission critical failure. Baumann in [3] stated that: "Left unchallenged, SEEs have the potential for inducing the highest failure rate of all other reliability mechanisms combined".

Advanced microprocessor and memory semiconductor devices used in modern avionics exhibit an increased susceptibility to SEEs caused by ionising radiation from the following two main sources:

- Cosmic rays from space (10^{+10} of a metre and beyond) that are individual energetic particles that originate from a variety of energetic sources ranging from our Sun to supernovas and other phenomena in distant galaxies all the way out to the edge of the visible universe. Although the term cosmic ray is commonly used, this term is misleading because no cohesive ray actually exists. The majority of cosmic rays consist of the nuclei of atoms (atoms stripped of their outer electrons) ranging from the lightest to the heaviest chemical elements. In terms of composition about 90% of the nuclei are hydrogen, therefore just single protons, 9% are helium, alpha particles with the remaining 1% a mix of heavier element nuclei, high energy electrons, positrons and other sub-atomic particles. Within the atmosphere the three most important parameters used to define the variability of the particle flux at a specific location are: altitude, latitude and energy. Within the field of cosmic ray physics altitude is expressed in terms of atmospheric depth, which is the mass thickness per unit of area in the Earth's atmosphere. Cosmic rays can be broadly divided into two main categories, primary cosmic rays and secondary cosmic rays. Primary cosmic rays are particles accelerated at astrophysical sources and generally do not penetrate the Earth's atmosphere. Secondary cosmic rays are created when primary cosmic rays collide with oxygen and nitrogen nuclei in the atmosphere and break into lighter nuclei in a process known as cosmic ray spallation.

- Alpha particles from radioactive impurities in the materials of which device are made (10^{-10} of a metre and below). They are doubly ionised helium atom consisting of two neutrons and two protons that can also be described as a helium atom that has been stripped of its electrons. When an alpha particle travels through a material it will lose kinetic energy primarily through interactions with the materials electrons, leaving a trail of atoms with "kicked out" orbital valence electrons. This process is called ionisation and it can be described as the physical mechanism that converts an atom or molecule, into a positively or negatively charged state by either adding or removing charged particles. The resulting atom is then referred to as an ion, or more specifically a cation if positively charged or an anion if negatively charged. The issue of alpha particle generating source contaminates first arose in the late 1970s when Intel discovered high soft error rates in new DRAMs when the integration density increased from 16K to 64K. The problem was traced to a semi-conductor packaging plant that had just been built downstream from an abandoned uranium mine. The ceramic packages were being contaminated by radioactive contaminants in the water. Low energy alpha particles are emitted from the decay of trace radioactive materials in semi-conductor device and packing materials.

The relationship between the radiation particles and the failure mechanisms of the single events upsets is shown in the Table below. [4]

Radiation Type	**Radiation Source**	**Method of Charge Deposition**	**Failure Mechanism**
Thermal neutrons	Secondary cosmic ray neutrons	Indirect Ionisation	Interaction between thermal neutrons and materials containing the Boron-10 isotope creates secondary ionising particles.

Low energy alpha particles	Radioactive decay of uranium and thorium impurities located within the device materials.	Direct Ionisation	4 to 9 MeV alpha particle, creating an electron hole funnel.
High energy neutrons (10 MeV - 1 GeV)	Secondary cosmic ray neutrons	Indirect Ionisation	High energy neutron collisions with silicon nuclei.

Table: Failure Mechanism Summary

As the reliance on avionics systems within aircraft increases so do concerns regarding the reliability of these systems, particularly for those systems, which are considered safety critical. Hence, to take the appropriate mitigating actions and enable decisions to be made at the design stage a method need to be devised that will facilitate the calculation of soft errors rates due not only to quiescent conditions, but also to take into account more exceptional solar influenced events.

The research currently undertaken within the MIRCE Akademy has two main objectives; the development of an SEE functionability prediction model and the use of the model to investigate the influence of space weather, flight route and a multitude of other aircraft and system design factors on the resultant shape of the distribution of SEE initiated failure events through time. The main areas of research are: the investigation on the influence of the aircraft structure on the internal neutron flux spectra at specific inside locations of the architectures of future commercial aircraft and the evaluation of the methods and techniques used by the electronics industry today to assess their suitability for the inclusion into the SEE functionability prediction model. A plethora of device and circuit level simulation methods exist together with a range of empirical techniques exist that could be used at various indentures levels. The integration of these methods into an SEE functionability model may lead to an improved understanding of SEE fault propagation mechanisms resulting in a more accurate prediction of failure events at system level. The final goal is the creation of an innovative SEE functionability prediction model that will enable the future behaviour of an avionics system to be predicted for a whole host of different external parameters such as the extremes of space weather or different flight routes. Furthermore the model should allow system designers the flexibility to examine the full range of system design options such as device selection, system configuration and SEE reduction solutions to allow early functionability improving design decisions to be made, as least investment in time and resources.

Time to Choose between Scientific and Administrative approach to Reliability

The main objective of this paper was to present the authors approach to Reliability, one that is based on the laws of science. I do not believe in the existence of parallel universes where the laws are either ignored or bent to accommodate administrative or contractual requirements. A prime example of the later is the well accepted model of system reliability that requires the acceptance of “alternative universes” to support the argument that the components and consequently systems possess a constant, time independent, failure rate, as described by the equation 2. This approach stems from neither science nor observation, but from imaginary steps envisaged in the minds of its proponents who allowed all laws of science to be suspended. However, this view is in direct opposition to the observed functionability phenomena like corrosion, fatigue, creep, wear, quality problems and many other time dependent physical processes that clearly demonstrated that the components/system reliability for a stated period of time could have increasing, constant and decreasing probability of success in respect to the age of a system, consisting components and maintenance policies applied, as the science based approach caters for through the reliability function defined by the equation 1.

Finally, it is essential to distinguish the scientific formulation of the motion of functionability through the life of a system, contained in Mirce Mechanics and presented in this paper, from administrative approach that is based on reliability models of systems that are created to demonstrate the contractual compliance of the legally binding acquisition processes. As science is the proved model of reality that is confirmed through observation, the summary message of this paper to reliability professionals is to move from then universe in which the laws of science are suspended to the universe that is based on the laws of science in order for their predictions to become future realities.

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Appendix 1: Mirce Mechanics Concept

Mirce Mechanics - scientific study of the motion of functionability through the life of a man made and managed system to:

- Experimentally determine the pattern of the motion
- Scientifically understand mechanisms of the motion
- Mathematically defined laws of the motion
- Predict the pattern of the motion of a given system

Functionability, the ability of being functional, is the fundamental property of in-service performance of any system. It is an emergence property of a system, in time domain, resulting from the complex interactions of natural phenomena, such as fatigue, corrosion, creep, wear, humidity, wind, hail, foreign object damage, solar radiation and similar, on one hand and from human actions taken in respect to the type, content and timing of operational, maintenance and support processes, on the other.

To achieve the above objectives Mirce Mechanics concept, principles and methods have evolved from the experimental, theoretical, computational and applied aspects of research, each of which is briefly described below.

Experimental Mirce Mechanics focuses on the determination of the pattern of the motion of functionability through the life of a system resulting from the occurrence of functionability events. Existing experimental and observed data clearly demonstrate that the motion of functionability through life of a large number of "identical" systems deliver a large number of different functionability patterns, while delivering “identical" functionality. Consequently, it is statistical experiment that requires the use of statistical methods to calculate the average pattern and associated measures. However, as statistics does not study the causes of statistical behaviour it is the task of Mirce Mechanics to scientifically understand the mechanisms that cause the motion of functionability in time. Thus, functionability phenomena that cause occurrence of positive and negative functionability events are subjected to the analyses within physical scale between 10^{-10} metre (for the understanding atomic and molecular phenomena) and 10^{+10} metre (for the understanding of cosmic and environmental phenomena).

Theoretical Mirce Mechanics focuses on the mathematical definition of the patterns of the motion of functionability through the life of a system. Mathematically formulated law of the motion, in respect through time, which accurately represents the observed patterns, is defined by the expression, named Mirce Functionability Equation, which has been developed by Dr J. Knezevic at the MIRCE Akademy. It defines, in the probabilistic terms, the expected patterns of functionability trajectory and associated measures for a given system, operational rules and conditions. Although the laws of probability are just as rigorous as other mathematical laws they are not able to predict the motion of functionability through the life of each individual system, they can only predict the probability of each individual system being in a given functionability state at a given instant of time.

Computational Mirce Mechanics focuses on the quantitative evaluation of Mirce Functionability Equation for a given system and given in-service rules and conditions, as the analytical solutions to these equations are too complex to be solved mathematically. Consequently, it is the task of Mirce Mechanics to develop effective computational methods that will enable construction of models that accurately represent the observed reality of system behaviour, rather then to simplify system reality to cope with mathematical limitations. The Monte Carlo method has proved very successful in Quantum Mechanics for finding practical solutions to multi-dimensional integral equations that are of similar nature to those of the Mirce Mechanics.

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