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"MIRCE Science is a theory of the motion of working systems through MIRCE Space resulting from any functionability actions whatsoever, used for Management of In-service, Reliability, Cost & Effectiveness."
Dr J. Knezevic, Founder, 1999

Space Weather as a Mechanism of Motion of Autonomous Trains in MIRCE Science

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Abstract

The main objective of this paper is to draw attention to the scientific approach to reliability and safety of autonomous trains, promoted by MIRCE Science, as guidance for the design engineers and operational managers of the future driverless rail transportation systems. Hence, scientific understandings of the mechanisms that cause undesirable events during their operation by surrounding natural environment are required. This paper focuses on already experienced negative impacts of space weather on reliability and safety of technological systems like power networks, aviation, ships, pipelines, digital control systems and similar. The events presented in this paper should be served as the lessons learned that must be considered during the development of the operational concepts of the future autonomous trains and technologies used. Then and only then, accurate and meaningful reliability and safety actions could be taken by design engineers and operational managers that should be able to deal with potentially harmful consequences of the space weather on the working effectiveness of autonomous trains.

Key words: MIRCE Science, functionability actions, space weather, autonomous trains

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1. Introduction

The philosophy of MIRCE Science is based on the premise that the purpose of the existence of any working system is to do work. The work is considered to be done when the expected measurable function is performed through time. MIRCE Science focuses on the scientific understanding and description of the physical phenomena and human rules that govern the motion of working systems through MIRCE Space[1]. A full understanding of the mechanisms that generate this motion is essential for the accurate predictions of the expected work done by a given working system type using the mathematical scheme of MIRCE Science. [1]

An autonomous train, like all other autonomous systems, is equipped with advanced technology that enables artificial intelligence to "think" and move by itself. This is achieved with sensors and software that identify its exact position, review its speed at any time, detect obstacles on the track, monitor its surroundings and many other relevant issues. They are becoming more and more common, from the metros and trams in city centres to the 2 kilometres long freight train, pioneered by Hitachi Rail. It has no driver, but it has a range of AI enabled cameras and machine learning algorithms that tell it what to do when it 'sees' a kangaroo, encounters a level crossing, or needs to adjust its speed to the gradient of the terrain, at Rio Tinto mine in Australia. [2]

On 27th February 2023 a powerful solar storm delayed the SpaceX rocket launch as a huge amount of charged solar particles reach Earth. In February 2022 SpaceX lost a batch of 40 satellites after launching them right into a relatively mild geomagnetic storm. The interactions of these particles with the upper atmosphere caused the atmosphere to swell as the density of gases at higher altitude increases and spacecraft experience more drag. Since SpaceX launches Starlink craft into very low altitudes and then uses the onboard propulsion of satellites to raise their orbit, this additional drag was too much and satellites were lost. [3]

Even more, the same solar storm temporarily disrupted work of multiple oil rigs in Canada, as GPS signals were too inaccurate. The electronics in the tool that determines which direction and inclination the drill bit should be going was receiving so much interference from the storm that its readings were unreliable. [4]

The railway transport system heavily depends on the availability of other critical infrastructures such as power, signalling, communications, and navigation systems for operations. Many research studies have shown that these technologies were and could be disrupted by impacts of space weather generated phenomena.

Consequently, the main objective of this paper is to draw the attention of the railway industry to the MIRCE Science approach to reliability and safety of the future autonomous trains whose working performance could be significantly affected by the space weather. Impact of the space weather on in-service reliability of avionics is discussed in the paper, as they were the first earthly systems to be affected. It is essential to understand the potential impacts of space weather on the operation of the technologies and sensors used that are "nerves" of the operation of the autonomous trains in the future. Only then, meaningful reliability and safety engineering actions could be taken towards reduction of

[1] MIRCE Space is a conceptual 3-dimensional coordinate system containing a sequential motion of a working system through quantised functionability states in time and probability of being in them. [1]

the probability of occurrences of the damaging effects of space weather on autonomous trains during their working lives.

2. The concept of Autonomous Train

In 1968, London Underground opened the Victoria Line that had the first fully automated trains running on it. A driver was still present in the cabin, and there were still manual controls which could override the automation in an emergency, but the main job was opening and closing the doors, something that could not be safely done remotely.

It wasn't until the arrival of the Port Liner in Kobe, Japan, in 1981 that the world had a fully autonomous public railway. A few years later a similar system was built in Lille, Northern France. Today there are many autonomous public transportation systems around the world, with a higher degree of automation than ever, on inter-city high speed train services. However, there is still always a driver or engineer on board, with various levels of control, as well as overall management of the train, equivalent to a ship's captain.

2.1 Levels of autonomous trains

While full driverless autonomy is certainly technically possible, and is applied on various routes world-wide, it still accounts for a small percentage of trains running today. New trains are still being designed and built with fully equipped driver cabins. However, looking to the future the industry has a categorised the Grades of Automation (GoA) for trains, as follows:

- GoA0: All driving done by a human, no autonomy.

- GoA1: A human starts and stops the train, but it can automatically travel in between, with the driver able to intervene in an emergency.

- GoA2: The driver remains in the train to override the transportation system if necessary and to perform procedures like checking the platform is clear of passengers before initiating the start sequence, but the train drives from stop to stop automatically.

- GoA3: A person, who can take over the controls if needed, is always on board, but not necessary in the cabin, while checking tickets, making announcements, opening and closing doors and so forth. However, the train can, and does, drive itself.

- GoA4: Neither driver nor any staffs are required to be in the train, at any time, as the full automation manage all passenger safety and driving activities.

Although reliability and safety are a paramount for rail transportation, nowadays there is a push towards automation that is facilitated by remote monitoring, on-train sensors, fail-safe computer based algorithms for vehicles and networks, all of which are considered sufficiently adequate to provide the expected level of railway services.

The natural ability of drivers to notice, interpret and take action on-track hazards, including other trains, requires several hundred metres distance between most trains. However, on automated trains with modern hazard management that reaction and decision time is not required, which means that they can travel closer to each other and still stop safely in an emergency, enabling higher throughput.

The 23 June 2023 the 1st stage of Honolulu Rail Transit system was opened, which is the first fully autonomous system in the US. Hitachi Rail launched a driverless metro system in Copenhagen, a safe, fast and comfortable metro system that pioneers autonomous train operation. The final giant leap will be to apply GoA4 to high-speed intercity passenger trains, although there are few signs of that happening in the experimental projects. The technology certainly exists, but the cost of re-engineering large networks and their infrastructures might prove decisive.

3. MIRCE Science Fundamentals

MIRCE Science is a theory of the motion of working systems through MIRCE Space resulting from any functionability actions whatsoever and the actions required to produce functionability related motions. According to MIRCE Science, at any instant of calendar time, a given working system could be in one of the following two macro states [1]:

Positive Functionability State (PFS), a generic name for a state in which a working system is able to deliver the expected measurable function(s),

Negative Functionability State (NFS), a generic name for a state in which a working system is unable to deliver the expected measurable function(s), resulting from any reason whatsoever.

In MIRCE Science, work done by a working system is uniquely defined by the trajectory generated by its motion through MIRCE Space. That motion is driven by functionability actions, which are classified as:

1. Negative Functionability Action (NFA), is a generic name for any natural process or human activity that compels a system to move to a NFS. Typical examples are: thermal ageing, actinic degradation, acid reaction, bird strike, warping, abrasive wear, suncups formation on the blue ice runway, fatigue, pitting, thermal buckling, photo-oxidation, production errors, strong wind, maintenance error, hail damage, lightening strike, COVID-19, quality problems in production or installation, tsunami, sand storm and so forth.

2. Positive Functionability Action (PFA), is a generic name for any natural process or human activity that compels a system to move to a PFS. Typical examples are: servicing, lubrication, visual inspection, repair, replacement, final repair, examination, partial restoration, inspection, change of operational mode, postponed operation, modification, cannibalisation, refurbishment, condition monitoring, packaging, diagnostics and similar

The main objective of MIRCE Science is the scientific understanding of mechanisms that govern positive and negative functionability events. That represents a real challenge, as the answers to the question “what are the natural and human processes that lead to the occurrence of given functionability events” have to be determined. Without accurate answers to those questions the prediction of their future occurrences is not possible, and without the ability to predict the future, the use of the word science becomes inappropriate.

Research studies conducted at MIRCE Akademy[2] by staff and students had shown that any serious studies of the functionability mechanisms have to be based between the following two boundaries [1, 13,15]:

- 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 physical phenomena that take place in the natural environment and the physical mechanisms that govern functionability events during the life of working systems.

Space weather is a phenomenon of the natural world that directly impacts the reliability of working systems in general and potentially autonomous trains in particular. This paper therefore considers major properties of space weather that impacts the amount of work done by autonomous trains.

3.1 Space weather as a negative functionability action in MIRCE Science

Negative functionability action is a generic name for any natural process or human action that compels a working system to move to a NFS, some of which are mentioned earlier in the paper. Space weather is one of the numerous natural actions that have a negative impact on the work done by an autonomously working system. Their physical occurrences are manifested through occurrences of negative functionability events. These are observable instances of time at which working systems stops delivering expected measurable function(s). [1]

Space weather events have always occurred, but as the biggest impacts are arguably on technology driven systems, it is only in modern times that our attention is drawn toward their susceptible threats. Different systems across the globe are exposed to varying levels of risk depending on their technical design, location and the type of space weather they are susceptible to. It is a reliability and safety engineering challenge to ensure that future systems are designed with appropriate provisions to minimise the risk posed by space weather. [7]

Until the early 1980s the space weather phenomena was only observed in orbiting satellites. Then they began to be noticeable in electronic devices related primarily to radiation concern for avionics, a term derived from the expression "aviation electronics", concerned with the development and production of electronic instruments used in aircraft and spacecraft. [8]

A Single Event Effects, SEEs, is the principal space weather phenomena affecting avionics devices. The Single Event Upset, SEU, is a NFE that is occurring when a sole incident particle creates a charge disturbance of sufficient magnitude in a memory cell, flip-flop, latch or register to reverse or flip its currently stored data state. Alternatively, in logic or

[2] for more information follow the link: http://www.mirceakademy.com/news/2/15/MIRCE-Functionability-Actions/

support circuitry a transient voltage pulse can be generated that, on the right conditions, can propagate through the logic of the device and become latched into a memory cell. Voltage spikes on power supply lines and noise can also cause transient errors. However, appropriate shielding and filtering design measures can suppress these types of disturbances. [12, 14]

Space weather generated radiation can affect electronic devices as the consequence of a single energetic particle strike, termed ‘single event’ or as multiple strikes over an extended period of time. The effects due to multiple events, Total Ionisation Dose, TID, and displacement damage manifest gradually in electronic components as damage is accumulated over time. These total dose effects and hard SEEs whilst relevant to electronic systems operating in the harsher space environment have a negligible effect on current semiconductor devices used in the terrestrial environment.

Multiple Bit Upset, MBU, is the second most prevalent SEE that occurs when a single particle causes the upset of two or more memory cells. Fortunately MBUs only form a fraction of the total number of SEUs, thus they have little significance except for memory architectures employing Error Detection and Correction, EDAC, techniques. In these circumstances, dependent on the type of error correction technique employed, multiple bit errors could have significant consequences if the protected memory is used for flight or mission critical applications. MBUs are generally assumed to attribute 3% of the total upset rate. [12]

The following two negative functionability events account for the majority of the remaining proportion of SEEs affecting avionics devices, thus:

Single Event Functional Interrupt, SEFI, that occurs when an upset initiates an Integrated Circuit, IC, test mode or reset mode that causes the device to temporary loose functionality.

Single Event Latch ups, SELs, arise when an incident particle creates a charge disruption sufficient enough to effectively short circuit the device resulting in its permanent change of state or in some circumstances permanent damage if excessive current flows as a result of the latch-up.

The last SEE of avionics relevance that can generate soft errors in the core logic of microprocessors and microcontrollers is the Single Event Transient, SET. They are transient and non-destructive in nature and are capable of producing a soft error, (i.e. the storage of an erroneous data value in registers, memories or latches) only if it is propagated through the logic pathways of the device. [9]

4. Placing space weather in MIRCE Functionability Equation

MIRCE Functionability Equation is a mathematical description of the motion of the working systems through MIRCE Space, caused by any action whatsoever, is defined as following expression [1]:

$$y(t) = 1 - \sum_{i=1}^{\infty} F_S^i(t) + \sum_{i=1}^{\infty} O_S^i(t), \quad t \geq 0 \qquad (1)$$

In the above equation $F_S^i(t)$ is a cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the sequential negative functionability event, $TNE_S^i(t)$ of a system considered. In MIRCE Science it is defined by a following convolution integral:

$$F_S^i(t) = \int_0^t O_S^{i-1}(x) dF_{S,i}(t-x), \qquad i = 1, \infty \qquad (2)$$

where: $F_{S,i}(t)$ is a cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the i_{th} negative functionability event, $TNE_{S,i}(t)$ of a working system considered. The number of these functions is equal to the number of NFA that generate NFE occurring during the in-service life of working systems, briefly mentioned above. In the case that this random variable is governed by the impact of space weather it is denoted as $TNE_{S,i,SW}$, and it is defined by the following expression:

$$F_{S,i}(t) = P(TNE_{S,i,SW} \le t) = \int_0^t f_{S,i,SW}(t) dt \qquad (3)$$

where; $f_{S,i,sw}(t)$ is a probability density function of the random variable that defines the time to the occurrence of i_{th} negative functionability event, which in this specific example is a space weather. The above equation is in the most generic form and as such covers all possible variations and impacts of space weather, which means each specific generating NFA has its own mathematical expressions for each occurring event.

In the equation (1) $O_S^i(t)$ is a convoluted form of cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the consecutive positive functionability event, $TPE_S^i(t)$ of a system considered. In MIRCE Science it is defined by the following convolution integral:

$$O_S^i(t) = \int_0^t F_S^i(x) dO_{S,i}(t-x), \qquad i = 1, \infty \qquad (4)$$

where: $O_{S,i}(t)$ is a cumulative distribution function of the random variable that mathematically represents the time to the occurrence of the i_{th} positive functionability event, $TPE_{S,i}(t)$ of a system considered. The number of these functions is equal to the number of NFA that generate NFE occurring during the in-service life of working systems, briefly mentioned above. In the case that this random variable is governed by the impact of a positive action taken in response to the occurred space weather generated NFE on the autonomously working system. It is denoted as $TPE_{S,i,SW}$, and it is defined by the following expression:

$$O_{S,i}(t) = P(TPE_{S,i,SW} \le t) = \int_0^t o_{S,i,SW}(t) dt \qquad (5)$$

where; $o_{S,i,sw}(t)$ is a probability density function of the random variable that defines the time to the occurrence of i_{th} positive functionability event, which in this specific example is a space weather responding action. The above equation is in the most generic form and as such covers all possible variations and impacts PFA that could be taken to return a system to PFS after impacts of space weather generated NFA, which means that each action has its own mathematical expressions for each specific application.

Possible space weather generated actions that could cause occurrences of NFEs and thus impact the motion of autonomous trains through MIRCE Space are addressed in the remaining part of the paper.

5. The concept of Space Weather

Space weather term refers to the environmental conditions in Earth's magnetosphere, ionosphere and thermosphere due to the Sun and the solar wind that can influence the functioning and reliability of space-borne and ground-based systems and services or endanger property or human health. Space weather deals with phenomena involving ambient plasma, magnetic fields, radiation, particle flows in space. In addition to the Sun, non-solar sources such as galactic cosmic rays can be considered as a part of space weather since they alter space environment conditions near the Earth. [5]

Space weather science is a developing field and its impacts upon modern society have only recently come in to the fore as results of dependencies on technologies vulnerable to solar phenomena increases. Therefore, significant research efforts are made to better understand potential impacts of severe space weather events.

The sun is a dynamic star. Its surface boils at over 5,500 degrees Celsius, with complex electric and magnetic fields twisting, winding and plunging in and out of the depths. This intricate relationship between the superheated plasma of the sun and its own magnetic fields creates the conditions for solar storms. These events, including flares, eruptions and coronal mass ejections, release tremendous amounts of energy into the solar system. Sometimes the releases take the form of pure radiation, whereas sometimes entire blobs of sun stuff launch from the surface, moving slowly toward the planets. Often, the sun launches storms of tiny, charged particles known as solar energetic particles, SEPs, electrons and protons travelling at nearly the speed of light.

During periods of intense solar activity, SEPs can slam into Earth, penetrating its magnetic field and even punching through the atmosphere, raining deadly radiation onto the surface causing electronics to get scrambled, and sensors to get damaged.

The three constituent elements of a solar storm and their resultant space weather manifestations are:

- Solar flares: magnetically initiated explosions that occur at or near the surface of the Sun that release intense bursts of electromagnetic radiation in the form of x-rays, ultraviolet and radio emissions, which can cause disruptions to the Earth's ionosphere leading to radio and communications interference.

- Geomagnetic storms: large disturbances in the Earth's magnetic field caused by changes in the solar wind and interplanetary magnetic field, IMF structure.

- Coronal mass ejections, CMEs: a result of the twisting and realignment of the sun's magnetic field. As magnetic field lines "tangle" they produce strong localised magnetic fields that can break through the surface of the sun at active regions.

To provide an appreciation of the temporal characteristics of the Sun's effects on the radiation environment, the arrival times of each solar storm component are very briefly stated below:

- X-Rays and radio waves travel from the Sun at the same speed as visible light, hence they take approximately 8 minutes to reach Earth.

- The speed of protons during solar particle ejections is dependent on energy level and therefore typically takes between 15 minutes to a few hours to generate atmospheric and ground level particle enhancements.

- The solar plasma cloud of CMEs takes between 2 and 4 days to impact the Earth's geomagnetic field and generate a geomagnetic storm that may take several days or even weeks to recover.

6. Impact of space weather on functionability of autonomous trains

The amount of work done by autonomous trains during a stated time, W(Tst), is not driven by their functionality performance, it is driven by their functionability performance, defined by equation (1). Hence, the expected amount of work done by a working system could be determined by making use of the following:

$$W(Tst) = \int_{0}^{Tst} y(t)dt \qquad (6)$$

To do the work an autonomous train has to be in PFS and for that to happen its supporting infrastructure like, power provisioning, signalling,communications, navigation, positioning and similar systems must be also in PFS. However, the digital technologies used within supporting systems have increased the risk of adverse effects caused by the space weather on their functionability.

For example, the power-grid is critical for train's functionality because of its immediate impact on the railway network, as well as potential affects on other systems within railway stations. From a safety criticality standpoint, the most significant systems that may be affected by geomagnetically induced current, GIC, are signalling and traffic control systems. This problem exists due to the increase in lengths of track-circuit and longer length of trains. Other train supporting equipment such as heating systems, switching actions can also be possibly susceptible to GIC are wayside cables, telecom and line-side circuits, backup systems, batteries, condition monitoring systems, point circuits in switching, crossings and location devices. [11]

Autonomous trains control systems used for communications are relying on mobile phones and wireless technology, which is also susceptible to interference from solar radio bursts. The same applies to the speed and position controlling systems that communicate movement of trains. Interference from radio bursts could cause the transition of the functional train to NFS stopping it from doing the expected work. [6]

A research project that investigated the effect of solar storms on railway signals has shown that fluctuations in space weather are disrupting train signals and causing significant delays. To track the location of trains, a railway line is split into small, consecutive segments called 'blocks' with an average length of 1-2 km. Each block is tied to a signal that indicates the presence of a train in that block. The signals are controlled by relays that detect currents in the system, which turn signal to green if the block is empty and a current is detected or to red if the block is occupied and no current is detected. [5]

According to [16] solar storms can off-set the balance of currents controlling the light signals on train lines, causing lights to show clear sections as occupied with a red light. Evidence shows that stronger solar storm cause more signals to malfunction, thus increasing the amount of time the train is delayed. A team of researchers at the University of Lancaster has modelled the impacts of solar storms on two segments of the UK railway network, namely a South-North line from Preston to Lancaster and a West-East line from Glasgow to Edinburgh. One of the objectives of this research is to determine how strong a storm needs to be to turn a red signal back to green, which is very hazardous scenario potentially leading to crashes. Solar storms can off-set the balance of currents controlling the light signals on train lines, causing lights to show clear sections as occupied with a red light. Evidence shows that stronger solar storm cause more signals to malfunction, thus increasing the amount time the train is delayed. Technological problems can occur as a result of solar storms with a range of strengths: from medium storms with electric field strengths of 2V/km to strong storms at 4V/km. In the past, values of higher than 7 V/km have been detected along railways in Sweden. Estimates of extreme solar storms have predicted events with strengths of up to 20 V/km. Interestingly, the results suggest that signalling failures can occur even with moderate storms. So, while these estimates are unsettling, there is still cause for concern without these extreme storms. The continuation of this research is expected to provide the answer to the question, how strong a storm needs to be to turn a red signal back to green, which is a hazardous scenario potentially leading to crashes. [16]

7. Space weather forecasting

As almost all aspects of human life on Earth become ever more dependent on technology and systems such as satellites, Global Navigation Satellite System, Global Positioning System, power and radio communications, the threats of a severe space weather event are increasing in importance. Therefore, space weather prediction is of crucial importance to power companies, satellite operators and all modes of transport.

For example, a severe space weather event service was added to the United Kingdom's National Risk Register of Civil Emergencies in 2011. The Met Office, the national meteorological service for the UK, was given ownership of that task in 2013 and set up the Met Office Space Weather Operations Centre[3], MOSWOC, to provide space weather alerts, warnings, and guidance to the UK government and general public. The centre was officially opened in 2014 October, although 24/7 operational services commenced in 2014 April. MOSWOC provides flare forecasts to users multiple times daily as part of their space weather service. [10]

[3] https://www.metoffice.gov.uk/weather/learn-about/space-weather/what-is-space-weather

To address the potential dangers of solar activities on humans and technology on Earth, in 2023 NASA provided five years' worth of funding for CLEAR, a space weather forecasting centre at the University of Michigan. It will bring together astronomers and astrophysicists with a wide variety of specialities, ranging from observers to theorists, to address the challenge of SEP prediction. They will use theoretical models of the solar surface to predict when solar flares and coronal mass ejections, which launch SEPs, are likely to erupt.

8. Engineering mitigation for the impacts of space weather on autonomous trains

The main objective of this paper was to draw the attention of design engineers of autonomous trains to the impact of the space weather on their in-service reliability and safety. These impacts have been determined by applying principles of MIRCE Science to the process of the motion of autonomous trains through MIRCE Space.
Mitigation of the impacts of space weather on in-service reliability and safety of autonomous trains boils down to the following two opportunities:

- engineering out as much risk as is reasonably possible during the conceptual stage of the design of the future autonomous trains

- selecting operational strategies to deal with the residual risk during the in-service operation of autonomous trains

The impacts of both approaches could be quantitatively evaluated by making use of MIRCE Functionability Equation, given that all necessary information is available.
Needless to say, that is a real challenge, but it is essential to understand that functionability of autonomous trains is affected by the impacts of space weather driven functionability actions, on one hand and the impact of contemporary technologies used to control and manage their functionality, on the other. [13]

9. Conclusion

In summary, this paper states that reliability and safety considerations of autonomous trains must include the full understanding of the impact of space weather on their functionability performance. Then and only then, accurate and meaningful reliability and safety engineering predictions can become possible. These predictions are enabling design teams and operational managers to focus on the ultimate goal, which is the reduction of the probability of the occurrence of undesirable impacts of naturally occurring space weather phenomena on day to day operations of autonomous trains. It is necessary to point out that these phenomena impact all modern technological working systems like, power networks, aviation, satellite services, pipelines, digital controls and many others.

Further more, this paper advocates that the MIRCE Science physical scale from 10^{-10} metre to 10^{+10} metre must be used in order for the functionability events generating space weather mechanisms to be understood. Then and only then accurate predictions of functionability performance of autonomous trains could be obtained by making use of MIRCE Functionability Equation.

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