Annals of MIRCE Science

"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

MIRCE Science: Functionability Management of Autonomously Working Systems on Earth Affected by Impacts of Severe Space Weather on Orbiting Satellites

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Abstract

Harmful impacts of severe space weather on a large number of modern technological systems like: power networks, aviation, satellite services, radio communication and pipelines; have been observed and documented in the literature. Hence, the author concluded that space weather must have a similar impact on the digital technologies that will be used to provide the autonomy to the autonomously working systems in the future, like cars, trains, ships, drones and so forth. Thus, this paper briefly examined the space weather phenomena that could affect functionability of autonomously working systems by impacting provision of data provided by sensors contained in Earth orbiting satellites. Thus, MIRCE Science based philosophy made the author to conclude that functionability management of autonomously working systems in the future should focus on the protection of the sensors located in orbiting satellites from the exposure to continuously generating space weather in the Sun, by accurately monitoring their trajectories. Hence, when the damaging impact of severe space weather is predicted, the targeting satellite(s) should be temporarily moved to different orbital positions. This new type of functionability management is the only feasible solution for the provision of continuous operation of autonomously working systems of the Earth, as the physical execution of any maintenance tasks on sensors damaged by the impact of the space weather, within satellites, is impossible.

Key words: MIRCE Science**,** functionability of autonomous systems on Earth, impact of space weather on satellites, preventive maintenance by orbital repositioning

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0. Dedication

This paper is dedicated to the memories of my father, Milija Knezevic, who died a year ago, in his 99th year. He wholeheartedly supported my love for science and assisted my professional career on a few crucial junctions!

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 expected work through time. The work is considered to be done when a measurable function(s) is performed. It is a theory for the prediction of the motion of working systems through MIRCE Space, resulting from any functionability actions whatsoever and the actions required to produce any functionability motions. To that end a scientific understanding of mechanisms that generate positive and negative functionability events is an imperative. Without full understanding of these mechanisms the prediction of occurrences of functionability events is not possible, and without the ability to predict the future, the use of the word science becomes inappropriate.

To scientifically understand the functionability actions generated mechanisms of the in-service behaviour of several thousands of components, modules and assemblies of working systems in defence, aerospace, nuclear, transportation, motorsport and communication industries have been conducted at the MIRCE Akademy, by staff, students and Fellows. Results obtained had shown to the author that any serious studies of the functionability mechanisms have to be based between the following two boundaries [1]:

- 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 exists 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.

On 27th February 2023 a powerful solar storm, containing a large amount of charged solar particles, reached Earth and temporarily disrupted operations of several Canadian oilrigs, which was the very first time in living memory that the drilling operations were suspended. The cause of the interruption was the exposure of the digital sensors located in the Earth orbiting satellites to the space weather. Resulting impact was the in-accuracy of GPS data that were driving the electronics in the part of the equipment which determines the direction and inclination the drill bit is going. [2]

However, the response to the same storm of 27th February 2023 by the American Company SpaceX was to promptly delay the planned launch of the Starlink rocket. That was the direct result of the costly lesson learned from 3rd February of 2022 when 38 out of 49 satellites launched by SpaceX’s Falcon 9 rocket just perished! They were launched in Low Earth Orbit

(LEO) during a moderately strong geomagnetic storm.
Its magnetic cloud was traced back to the Sun as a halo that erupted on 29th January 2022 at 22:45 UT and travelled at a moderate speed of 690 km/s. The impact of the loss of the Starlink satellite systems had cost the company millions of dollars. Consequently, SpaceX has started paying greater attention to space weather forecasts and even became a regular supplier of the data from Starlink's onboard sensors to the U.S. National Oceanic and Atmospheric Administration (NOAA) to help them to improve the space weather forecasting models. [2]

An autonomously working system can be defined as a collection of mutually interactive entities put together to deliver at least one measurable function independently of human interaction by receiving its inputs from a set of electronic senses that are processed in accordance to established algorithms. Autonomous ships, trains, cars and similar systems are expected to operate independently of human interactions, by receiving inputs information from the range of physical sensors. Recent development of digital technologies enabled immense amounts of information to be compressed on small storage devices that can be easily preserved and transported. They have made fundamental changes to many aspects of human lives, including the creation of autonomously working systems. However, most of these digital sensors are managed by satellites that are orbiting the Earth, which get exposed and impacted by space weather. Thus, the ability to accurately maintain the continuously changing flow of information between the physical reality of autonomously working systems and the performance of their expected functions via Earth orbiting satellites are essential for reliable, safe and profitable day-to-day operation.

In summary, the main objective of this paper is to draw the attention of the operational managers to the MIRCE Science approach to the maintenance of the autonomously working systems of the future. It is totally different from all other known maintenance types as it is based on the accurate predictions of the occurrences of severe space weather generated by nuclear reactions taking place on the Sun and the execution of the preventing avoidance manoeuvres to protect the digital technology sensors located in the Earth orbiting satellites that are the providers of autonomy to autonomously working systems on the Earth.

2. The Concept of Space Weather

Terrestrial weather, manifested through physical phenomena like: wind, snow, rain, hail, thunder and lightening, has significant impacts on the operation of terrestrial systems. Physical impacts of these metrological phenomena are reasonably well understood and included in reliability analysis of the majority of systems deployed. [3]

Similarly, space weather is manifested through physical phenomena like: evolving ambient plasma, magnetic fields, radiation, flows of charged particle in space and similar. The effects of space weather, although unfelt by human senses, are observed in the interruption or degradation of functionality and performance of space located systems during their lifetimes. In addition, increased radiation due to space weather may lead to increased health risks for astronauts participating in manned space missions. The aviation sector may also experience damage to aircraft electronics and slightly increased radiation doses at aircraft altitude during large space weather events. In addition to the Sun, non-solar sources such as galactic cosmic rays can be considered as space weather since they alter space environment conditions near the

Earth. [4]

2.1 Impact of space weather on Earth's environment

The Sun is not a steady-state star. Its surface boils at over 6,000° C, with complex electric and magnetic fields twisting, winding and plunging in and out of the depths. It continuously undergoes changes, which sometimes could be extremely violent. These changes are transferred by the solar wind to the Earth and disturb its magnetic field. The regular changes in the level of solar activity over long-periods are known as the solar cycle. The duration of the solar cycle varies between 9.5 and 11 years. Usually, solar activity is measured by the number of sunspots on the solar surface. The solar cycle is also seen in the number and strength of the solar flares, which are resulting from tremendous explosions in a localised region on the Sun. In a matter of just a few minutes they heat material to many millions of degrees. [5]

The solar wind consists of ionized particles, mostly protons and electrons with a small admixture of helium ions. The density of solar wind is low, about 10 particles per cc. Solar wind also carries the Sun's magnetic field, which at the Earth's orbit has strength of only a few nT. The wind speed at the Earth's orbit is about 450 km/s or more. On its trajectory the solar wind encounters the Earth's magnetic field, which deflects the particles and shields the Earth from the direct effects of the solar wind.

Solar Storms happen when a Sun emits large bursts of energy in the form of solar flares and coronal mass ejections. These phenomena send a stream of electrical charges and magnetic fields towards the Earth at high speed, 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.

One of the effects of space weather striking Earth is the creation of the "northern lights" which are seen in the regions around the Arctic Circle. An adverse effect of solar storms is the disruption of satellites and other electronic means of communications. [6]

2.2 Types of solar storms

Solar Storms come in the form of the following types [7]:

- Solar Flares, which are manifested as a sudden flash of increased brightness on the Sun, usually observed near its surface and in proximity to a sunspot group. Powerful flares are often, but not always, accompanied by a coronal mass ejection. Even the most powerful flares are barely detectable in the total solar irradiance
- Coronal Mass Ejections (CME), which are 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. It is manifested through a significant release of plasma and accompanying magnetic field from the solar corona. They often follow solar flares and are normally present during a solar prominence eruption
- Geomagnetic Storm, which is a temporary disturbance of the Earth's magnetosphere caused by a solar wind shock wave and/or cloud of magnetic field that interacts with

the Earth’s magnetic field, caused by changes in the solar wind and interplanetary magnetic field (IMF) structure
- Solar Particle Events, or solar proton event (SPE), occurs when particles (mostly protons) emitted by the Sun become accelerated either close to it during a flare or in interplanetary space by coronal mass ejection shocks.

3. Impact of Space Weather on the Satellites Operations

Satellites are critically important for the successful operation of the autonomously working systems. Thus, it is essential to understand the consequences of their exposures to space weather, solar storms and consequential geomagnetic storms. When the Earth atmosphere absorbs energy from these space phenomena it heats up and expands upward. This expansion significantly increases the density of the thermosphere, the layer of the atmosphere that extends from about 80 km to roughly 1000 km above the surface of Earth. Higher density means more drag, which could cause a problem for them to maintain the altitude. [2]

Drag is just one hazard that space weather poses to space-based technological systems. Strong geomagnetic storms generate the significant increase in high-energy electrons within the magnetosphere, which penetrate the shielding on a satellite and accumulate within its electronics. The build-up of electrons can discharge in small lightning strikes and damage electronics, generating failures.

Penetrating radiation or charged particles in the magnetosphere, even during mild geomagnetic storms, can also alter the output signal from electronic devices. This phenomenon can cause errors in any part of a satellite's electronics and if the error occurs in critical parts, the entire satellite can fail.

Finally, space weather can disrupt the ability of satellites to communicate with Earth using radio waves. Many communications technologies, like GPS, for example, rely on radio waves. As the atmosphere continuously distorts radio waves by some amount, design engineers correct for this distortion when building communication systems. However, during geomagnetic storms, changes in the ionosphere, the charged equivalent of the thermosphere that spans roughly the same altitude range, will change how radio waves travel through it.

3.1 Impacts of space weather on digital technology driven sensors

Recent developments of digital technologies have made fundamental changes to the way humans live their lives. Among others, digital technology is a driving force behind all autonomously working systems, from passenger cars to spacecraft. In general, autonomously working systems can be defined as a set of entities that can operate independently of human interactions. They are performing expected functions by receiving inputs from a set of electronic senses that are processed in accordance to established algorithms. Thus, the ability to continuously exchange information relevant to the safe operation of autonomously working systems is of vital importance for their reliability. [2]

Autonomously working systems contain, among many other entities, communication and control parts that provide their autonomy. According to [8] the following elements are driven by digital technologies which are used in a range of physical sensors that control autonomous functions, such as:

- RAdio Detecting And Ranging (RADAR) is electromagnetic sensor used for detecting, locating, tracking and recognasing objects of various types at considerable distances
- LIght Detection And Ranging (LIDAR) is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth.
- Global Positioning System (GPS) is a network of satellites and receiving devices used to determine the location of something on Earth.
- Infra-Red (IR) camera is a measuring instrument used for non-contact measurements of the surface temperature of objects
- Inertial Navigation System (INS) is a self-contained navigational technique using motion sensors to calculate position, orientation, and velocity.

Consequently, the reliable and safe operation of autonomously working systems depends also on the reliability and accuracy of the controlling sensors listed above, which in turn, depend on reliability of Earth orbiting satellites in which they are imbedded and technology used. [9]

3.2 Impact of space weather on functionability of autonomously working systems

After a brief analysis of the space weather it became obvious that its continuous generating phenomena could have severe consequences on the in-service reliability and safety of autonomously working systems. Primarily, it was attributed to its impacts on the reliability and quality of controlling information provided by digital technology driven sensors contained in Earth orbiting satellites. Thus, the author has faced a question, "How to maintain operation of autonomously working systems on Earth in the cases of the failure of digital technology driven sensors located in Earth orbiting satellites, caused by space weather."

Clearly, it is physically impossible to perform any corrective maintenance task on the failed sensors in orbiting satellites, on one hand, and no satellites are designed to be brought back to the Earth for maintenance, on the other. Hence, the maintenance activities applied to the Earth operating systems are out of considerations.

Some of the impacts of solar weather can be reduced by shielding electronics from radiation or developing materials that are more resistant to radiation. The most frequently used materials for electromagnetic shielding include: sheet metal, metal screen, and metal foam. Any holes in the shield or mesh must be significantly smaller than the wavelength of the radiation that is being kept out, or the enclosure will not effectively approximate an unbroken conducting surface. However, there is only so much shielding that can be done in the face of a powerful geomagnetic storm, on one hand, and the adding weight to a spacecraft that is demanding more fuel, on the other.

The research performed in the context of MIRCE Science has shown that the maintenance of autonomously working systems against potential failures of the sensors located in Earth orbiting satellites from the impact of continuously generating space weather in the Sun, could be served the best if the satellites are temporarily moved from the trajectory of incoming harmful space weather generating particles. This is an equivalent of the well known preventive maintenance policy commonly applied to safety critical systems on the Earth. However, for this solution to work it is necessary to provide real time observations and predictions of space weather, equivalent to the 24/7 produced forecasts for the Earth weather. However, this could be the biggest obstacle for the practical implementation of the proposed maintenance policy for autonomously working systems.

4. Placing Space Weather in MIRCE Science

MIRCE Science is a theory of the motion of working systems through MIRCE Space caused any action whatsoever. It is used to predict expected work and risk of a given working system. It is achieved my making us of MIRCE Functionability Equation, defined by the author, in [10], thus:

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

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 ith consecutive 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 system considered. In the case that this random variable is governed by the impact of a space weather on the autonomously working system, it is denoted as $TNE_{S,i,SW}$, and it is defined by the following expression:

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

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 solar weather. The above equation is in the most generic form and as such covers all possible variations and behaviours of solar weather, which means that its users have to determine the applicable mathematical expressions for their specific application.

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 ith consecutive positive functionability event, $TPE_S^i(t)$ of a system or component 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. In this case the random variable considered is governed by the impact of a recovery action from occurred space weather on the autonomously working system. It is denoted as $TPE_{s,i,sw}$, and it is defined by the following expression:

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

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 space weather recovery action. The above equation is in the most generic form and as such covers all possible positive functionability actions that could be taken to return a system to PFS, after solar storms.

In summary, it is essential to stress the following two points:

- The above presented equations are a generic mathematical interpretation of the physical reality of the functionability of working systems. However, the accuracy of their predictions are in the hands of their users, whose knowledge and understanding of the physical reality guide them to the selection of the most appropriate mathematical functions to represent the impacting natural and human actions.
- The impact of space weather could be experienced at the component level, that might or might not affect the functionability of a working system considered or at the system level, that will affect the functionability of a system without a failure of any individual consisting component, as it was the case with 38 out of 49 Starlink satellites launched in February 2022.

The Equation (1) is the fundamental, and the only one known to the author, for normalising all feasible options of design, operation and maintenance options for the future autonomously working systems, at the time when their life cycle has been considered in respect of the expected deliverables, namely expected work and associated risk, for comparative reasons.

5. Predicting Space Weather

The successful management of functionability of satellites accurate prediction of space weather is essential, which is a very challenging task. The research performed by the author has shown that scientists are currently trying to find ways to increase the amount of lead time before a solar storm reaches Earth orbiting satellites. It could be achieved by closely monitoring the short energetic bursts of solar eruptions from the Sun's surface. Changes in the position, size and number of sunspots can also be used as indicators of solar activity, as there is a direct proportionality between the quantity of sunspots and the Sun activities. With enhanced observation and prediction techniques supported by rapidly developing applications of artificial intelligence (AI) the space weather predictions could be dramatically improved.

The globally recognised authority for forecasting and monitoring space weather is the Space Weather Prediction Centre, which is part of the US National Oceanic and Atmospheric Administration (NOAA). It estimates the impacts of geomagnetic storms, solar radiation storms and radio blackouts, as indicators of the severity of the coming solar events.
Each of the three event types is ranked on a five-point scale from minor (1) to extreme (5) to

provide descriptions of how events at the different levels might affect power systems, satellite operations, spaceflight operations, navigation systems and biological organisms.
It is interesting to point out that the NOAA had warned that, following a coronal mass ejection, a geomagnetic storm was "likely" to occur the day before or the day of the February 2022 Starlink launch. Totally unaware of the consequences the SpaceX went ahead with the mission, as scheduled.

Another well know institution is the National Centre for Atmospheric Research Mauna Loa Observatory located on the Big Island of Hawaii, at an elevation of 3397 m above sea, whose a round-based instrument called the K-Coronagraph is able to predict when harmful solar energetic particles are heading toward astronauts in the International Space Station. By measuring white light from the lower corona, the K-Coronagraph is able to detect the beginnings of solar activity that creates space weather, providing an extra 20 minutes of warning time. With this extra time astronauts can take safety measures, such as moving behind protective metal shields within the space station.

6. First Solar Storm That Simultaneously Impacts Earth, Moon and Mars

A coronal mass ejection that took place in August 2021 sent simultaneously energetic particles to Mars, the Earth and the Moon, emphasising the need to prepare human space missions for the dangers of space weather. [11] This CME caused an influx of highly energetic, and thus fast-moving, charged particles across the surface of these solar system bodies.

The detection of the same coronal mass ejection on these three different worlds for the first time highlighted the necessity for a better understanding of a mechanism that drives interaction between a planet's magnetic field and atmosphere. This is instrumental for the determination of methods for shielding autonomously working systems from such radiation.

The 2021 CME detection was the very first-of-its-kind. Interestingly, at the moment of the eruption, Earth and Mars were on opposite sides of the Sun with a distance between them of around 250 million km. This outburst was detected by the:

- Euglena and Combined Regenerative Organic-Food Production in Space (Eu:CROPIS) orbiter around Earth.
- ExoMars Trace Gas Orbiter (TGO) on Mars,
- Chang'e-4 Moon lander and NASA's Lunar Reconnaissance Orbiter (LRO) on the lunar surface

In October of the same year a coronal mass ejection was observed by the ESA/NASA Solar and Hemispheric Observatory (SOHO) experienced by a rare event called a "ground level enhancement" during which charged particles from the Sun travel fast enough to penetrate the magnetosphere and reach the ground. This particular occurrence is just the 73rd example of such an event since records began in the 1940s, and it remains the last to be recorded. [12]

As Mars and the Moon do not have a magnetic field, charged solar particles can strike their surfaces more often than on Earth generating a secondary radiation from their surfaces.

However, the atmosphere on Mars, while much thinner than Earth's, can still stop low-energy particles and slow high-energy particles.

7. Conclusion

Autonomously working systems are rapidly expanding. For example, maritime systems have been exposed to autonomy from surface to underwater vehicles being deployed for patrol, oceanographic and maintenance among other purposes. Furthermore, cargo ships projects involving coastal and ocean-going routes with different degrees of autonomy are being tested. In October 2021, the International Maritime Organization (IMO) approved an output to develop regulation for Maritime Autonomous Surface Ships (MASS). [13]

Space weather is natural phenomena that will continue to follow its own course of actions. As it has evidential impacts on the operation of autonomously working systems through digital technologies located in the Earth orbiting satellites, it is essential to understand it better. This paper has shown that space weather has impacted reliability and safety of a large number of modern technological systems, through real life examples. This fact led the author to conclude that space weather could have similar impacts on the reliability and safety of future autonomously working systems.

The research presented in this paper has shown that the maintenance of autonomously working systems against potential failures of the sensors located in Earth orbiting satellites from the impact of continuously generating space weather in the Sun, could be served the best if the satellites are temporarily moved from the trajectory of incoming harmful space weather generating particles. This is an equivalent of the well known preventive maintenance policy commonly applied to safety critical systems on Earth. However, for this solution to work it is necessary to provide real time observations and predictions of space weather, equivalent to the 24/7 produced forecasts for the Earth weather. However, this could be the biggest obstacle for the practical implementation of the proposed maintenance policy for autonomously working systems.

The future research that should enable safer and more reliable operation of autonomously working systems could go in two directions. The first, further improvement of the space weather prediction services towards provisioning of the early warnings in time sufficient for the maintenance action described in the paper to be taken by potentially endangered working systems. The second direction for the future research should be focused on innovative technologies and methods for designing equipment that is able to operate safely or protect autonomously working systems in the events of harmful impacts of solar storms in the future.

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