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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 **M**anagement of **I**n-service, **R**eliability, **C**ost & **E**ffectiveness."*

Dr J. Knezevic. Founder. 1999

Pre-Determined Debris Avoidance Maneuvers (PDAMs) as Mechanism of Motion of International Space Station through MIRCE Space

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Abstract

MIRCE Science is a theory of the motion of working system through MIRCE Space caused by any action whatsoever. The International Space Station is orbiting the Earth since 1998. At its orbit of 400 km there is huge concentration of orbital debris resulting from accidents, failures or, in some cases, deliberate destruction of human sent spacecraft. Due to their speed the debris present a serious treat to the safety of the station and its crew. Hence, the main objective of this paper is to present the accurate available record of the pre-determined debris avoidance maneuvers taken by the International Space Station thus far, through the perspective of MIRCE Science. The information regarding 24 functionability actions have been identified and presented in paper of out 38 recorded. Identifications of the tractable orbital debris that constituted negative functionability actions threatening the safety of ISS are cited. The cost of the resources used for the execution of avoiding functionability actions has been presented together with the estimated costs of the fuel consumed. Finally, this paper clearly confirms the fourth axiom of MIRCE Science that states "The probability that a functionable (working) system type will move to a negative functionability state at any instant of time is greater than zero", regarding possible collisions of ISS with orbiting orbital debris.

Key words: MIRCE Science, functionability actions, International Space Station, space debris, orbital debris, Pre-Determined Debris Avoidance Maneuvers

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1. Introduction

The philosophy of MIRCE Science[1] is based on the premise that the purpose of the existence of any human created working system is to do a work. The work is considered to be done when the expected measurable function is performed. At any instant of calendar time, a working system could be in one of the following two macro states:

- 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).

In MIRCE Science, work done by a working system is uniquely defined by the trajectory generated by its motion through MIRCE Space[2]. That motion is driven by occurrences of functionability events generated by the following functionability actions:

- Positive Functionability Action (PFA) is a generic name for any natural process or human activity that compels a system to move to a PFS.
- Negative Functionability Action (NFA) is a generic name for any natural process or human activity that compels a system to move to a NFS.

The time evolution of a working system through MIRCE Space is physically manifested through the occurrences of functionability events, which are classified as:

- Positive Functionability Event (PFE) that is a physically observable occurrence at which a working system moves to a PFS,
- Negative Functionability Event (NFE) that is physically observable occurrence at which a working system moves to a NFS.

To scientifically understand the mechanisms that generate functionability actions, positive and negative, analysis of the in-service behaviour of several thousands of items, modules, assemblies and whole systems in aerospace, nuclear, transportation, motorsport, communication, defence and other industries have been conducted at the MIRCE Akademy[3]. 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 has to be based with the following range:

- 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.

1 Knezevic, J., The Origin of MIRCE Science, pp. 232, MIRCE Science, Exeter, UK, 2017, ISBN 978-1-904848-06-6

2 MIRCE Space is a conceptual 3-dimensional coordinate system depicting a probabilistic trajectory of the motion of a working system through MIRCE functionability field. Knezevic (2017)

3 http://www.mirceakademy.com/news/2/15/MIRCE-Functionability-Actions/

The main objective of this paper is to present the Pre-Determined Debris Avoidance Maneuvers (PDAM) as a mechanism of the motion of the International Space Station (ISS) through MIRCE Space. Thus, the dates, circumstances and brief descriptions of 24 functionability events that were generated by of the detection of tractable orbital debris that were threatening the safety of ISS are cited. The cost of the resources used for the execution of avoiding functionability actions has been presented together with the estimated costs of the fuel consumed.

2. The International Space Station

The International Space Station came into existence on 6th December 1998, when the USA module Unity was deployed from space shuttle Endeavour was joined with Russia's Zarya module. Despite the fact that these two very different hardware pieces were run by computers that have never talked to each other and software that's only been tested in models, when assembled together it worked.

The whole process took a full orbit of Earth and it was completed 160 miles over China. The space station began hosting crews in November 2000. As of today, the ISS is the largest orbiting laboratory ever built. It is an international, technological, and political achievement by United States, Russia, Europe, Japan, and Canada.

The ISS orbits about 400 km above Earth. An international crew of seven astronauts resides and works while orbiting Earth at speed of 8 km/sec, about every 90 minutes.

3. Space debris and orbital debris

Spacecraft's are vulnerable to micrometeoroid and orbital debris (MMOD) impact. Each of these impacts has the potential to degrade performance, shorten the mission, or result in loss of the spacecraft. [18] Since 1957 humans have sent over 10,000 tonnes into orbit in total. Some of it became the debris in space as the result of accidents, failures or, in some cases, deliberate destruction. Also, many satellites also become obsolete, stop functioning, or were accompanied into space with detachable items, like rocket boosters, which are designed to stay in space. Consequently, space debris is generic name for any piece of equipment or debris left by humans in space.

NASA defines space debris as both natural meteoroid and artificial (human-made) orbital debris. Meteoroids are in orbit about the Sun, while most artificial debris is in orbit about the Earth (hence the term "orbital" debris). Orbital debris is the term for any object in Earth orbit that no longer serves a useful function. It includes non-operational spacecraft, derelict launch vehicle stages, mission-related debris, and fragmentation debris.

3.1 Size and quantity of debris

Based on statistical models produced by ESA's space debris office[4], it is estimated that in 2022 there were 36,500 objects larger than 10 cm, 1 million objects between 1-10 cm, and an extraordinary 130 million objects between 1 mm to 1 cm. These tiny objects could be anything from paint flecks from rockets or small fragments created from in-orbit impacts. However, despite their physical size, they can still cause an incredible amount of damage to spacecraft and satellites due to their travelling speed.

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4 https://sdup.esoc.esa.int/discosweb/statistics/

3.2 International identifiers for artificial objects in space

The Committee on Space Research (COSPAR) of the International Science Council (ISC) has created the international designator for identifying artificial objects in space, known as COSPAR ID. It consists of the launch year, a three-digit incrementing launch number of that year and up to a three-letter code representing the sequential identifier of a piece in a launch.

The United States Space Command (USSPACECOM) created North American Aerospace Defense Catalogue Number, NORAD ID in the order of launch or discovery to all artificial objects in the orbits of Earth and those that left Earth's orbit.

3.3. ISS as a source of orbital debris

During its operational life the ISS itself has become a source of orbital debris, both large and small. Most large debris were released during Extravehicular Activities (EVA), although manly by accidents.

By the 10th anniversary of the ISS, the U.S. Space Surveillance Network (SSN) had detected and catalogued 65 debris from the outpost, not including operational spacecraft releases, like the TNS-0 small satellite in March 2005.

Inadvertent losses ranged from a camera to a variety of tools to a complete tool bag to a foot restraint. Intentional debris releases included towels, equipment covers and carriers, hardware too large or too dangerous to return to Earth in a logistics vehicle, and an old space suit. Most of these objects fell harmlessly back to Earth in less than two months. The cumulative number of debris object-years is almost exactly 10, the equivalent of one piece of debris remaining in orbit for 10 years.

4. Pre-determined debris avoidance maneuvers of ISS as functionability action

NASA's long-standing guidelines require the ISS to maneuver if any satellite comes within a "pizza box"-shaped area of space surrounding the orbit of the station. The box is roughly 4 by 50 by 50 km with the ISS at the centre, according to agency officials. Tractable pieces in that orbital plane are roughly 5 cm in diameter, but even paint flecks can cause issues given the high velocities involved with objects in orbit.

When predictions indicate that any tracked object will pass close enough for concern and the quality of the tracking data is deemed sufficiently accurate, Mission Control centers in Houston and Moscow work together to develop a prudent functionability action for its avoidance. The collision risk is calculated many hours in advance of a potential collision based on the orbital elements of the debris object and potential target.

Successfully operated and finished pre-determined ISS debris avoidance maneuver PDAM and passing of orbital debris on the safe distance, will mark the moment in time when the ISS negative functionability action is finished, and ISS starting the positive functionability action to return to positive functionability state – normal operation mode.

4.1 ISS negative functionability actions between 1999 – 2003

During this period of operation the ISS performed 7 PDAMs, all of which are noted below:

27th October 1999: ISS performed collision avoidance action to prevent conjunction with Pegasus Rocket Body[5] (COSPAR ID: 1998-046K, NORAD ID: 25422). [1]

30th September 2000: ISS collision avoidance action to escape conjunction with Vostok Rocket Body[6] (COSPAR ID: 1971-031B, NORAD ID 5143). [1]

10th February 2001[7]: ISS/Space Shuttle collision avoidance action to prevent the conjunction with Electron 1 Debris (COSPAR ID: 1964-006, NORAD ID 87618). [1]

14th March 2001: ISS/Space Shuttle collision avoidance action avoiding conjunction with ISS/Shuttle Debris (COSPAR ID: 2001-010B, NORAD ID 26723) and Cosmos Rocket Body (COSPAR ID: 1990-078B, NORAD ID 20775). [1]

15th December 2001: ISS executed collision avoidance action to avoid conjunction with Cosmos Rocket Body (COSPAR ID: 1971-119B, NORAD ID 5730). Space Shuttle conducted action prior to undocking and conjunction. [1]

16th May 2002: ISS collision avoidance action avoiding conjunction with Cosmos Rocket Body (COSPAR ID: 1994-061B, NORAD ID 23279). [1]

30th May 2003: ISS collision avoidance action avoiding conjunction with MegSat (COSPAR ID: 1999-022B, NORAD ID 25722). [1]

4.2 ISS negative functionability actions between 2008 – 2015

There were no pre-determined debris avoidance maneuvers between 2004-2008. However, there were 18 PDAMs between 2008-2015. Those known to the authors are presented below:

27th August 2008: The ISS collision avoidance action occurred when a fragment from the Cosmos 2421[8] spacecraft was projected to pose a collision risk of 1 in 72. ESA's Automated Transfer Vehicle, the Jules Verne, performed the collision avoidance maneuver. [2]

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[5] Pegasus Rocket Body was launched on 2 August 1998. Flight ended-decayed on 15 December 2000. Launch site: Eastern Range Airspace, United States.

[6] Vostok Rocket Body SL-3 R/B. Launch date: 17 April 1971. Flight ended-decayed on 18 April 2001. Launch site: Plesetsk Missile and Space Complex, Russia, former USSR.

[7] Electron 1 (COSPAR ID: 1964-006A, NORAD ID 746) non-operational spacecraft with a cylindrical body 0.75 m in diameter and 1.3 m length from which antennas and six solar cell panels were extended. It was placed into an eccentric orbit to study the internal zone of the radiation belt. It was equipped with micrometeorite detectors, a proton detector, a mass spectrometer and instruments for recording the corpuscular emission and energy spectrum of electrons. It was launched on 30th January 1964 from Tyuratam (Baikonur Cosmodrome), USSR. Mass: 350kg. Electron 1 is still in orbit with minimum altitude-perigee of 418.1 km and peak altitude-apogee of 6272.7.

[8] This was one of more than 500 catalogued debris released from Cosmos 2421 during three major fragmentation events from March to June 2008, that took place only about 60 km above the orbit of the ISS. As these fragments decayed down towards the ISS orbit, the number of potentially threatening conjunctions each month increased by a factor of three.

October, 2010: The ISS was forced to action to avoid a potential collision with a piece of debris which had come off a 19-year-old NASA scientific spacecraft[9] only one month earlier. The collision avoidance action was successfully performed by the Progress M-07M logistics vehicle that docked at the aft port of the ISS Zvezda module on 12 September. [3]

2nd April 2011: The ISS performed collision avoidance action regarding a fragment from Cosmos 2251[10]. A small evasive maneuver action was done by the European Automated Transfer Vehicle 2 (ATV-2), which was docked at the aft end of the ISS complex on 24 February. The burn, which lasted 3 minutes and 18 seconds, was executed early 2 April (GMT), imparting a change in velocity to ISS of only 0.5 meters per second. [4]

29th September 2011: International Space Station dodging of orbital debris from the Russian Tsyklon rocket body. [17]

13th January 2012: International Space Station dodging of orbital debris. Avoiding conjunction with fragmentation debris from Iridium 33. [17]

28th January 2012: To avoid a possible conjunction with fragmentation debris from Fengyun-1C the ISS performed a required maneuver. [17]

12th November 2014: The ISS avoided satellite debris by activating engines of “Georges Lemaitre” Automated Transfer Vehicle for 3 minutes, 25 seconds. This pre-determined debris avoidance maneuver (PDAM) was done to move well away from a small piece of debris from a spent Chinese satellite (Yaogan 12) launched in November 2011. It was coordinated with Russian and European flight controllers, and raised the station’s altitude by 9/10 of a mile at apogee and 2/10 of a mile at perigee and left the station in an orbit of 262.3 x 252.0 statute miles. [5]

4.3 ISS negative functionability actions between 2020 – 2023

During this period 13 pre-determined debris avoidance maneuvers have been performed by ISS to protect it from identified orbital debris. Majority of them are listed below:

22nd September 2020: The ISS conducted PDAM by Progress 75 thrusters, with a 150-second reboost to avoid a possible conjunction with an unknown piece of space debris. Due to the late notification of the possible conjunction, the three Expedition 63 crew members were directed to move to the Russian segment of the station to be closer to their Soyuz MS-16 spacecraft as part of the safe haven procedure out of an abundance of caution. This functionability action raised the station’s orbit out of the predicted path of the debris at the estimated distance of 1.39 km. [6]

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[9] Since its decommissioning in late 2005, NASA’s Upper Atmosphere Research Satellite (UARS) had been gradually falling back to Earth. By September 2010 the 5.7-metric-ton spacecraft was in an orbit of 335 km by 415 km with an inclination of 57.0 degrees, when the U.S. Space Surveillance Network (SSN) discovered that a fragment had separated from the vehicle.

[10] Russian communications satellite which had accidentally collided with the U.S. Iridium 33 communications satellite in February 2009, producing more than 2000 large debris. Designated as Satellite Number 34443 in the U.S. Satellite Catalogue (COSPAR ID: 1993-036SL), the fragment had an apparent size of 10-15 cm.

3rd December 2021: The ISS orbit adjusted to dodge debris from old U.S. Pegasus[11] rocket (object 39915) rocket. Russian Progress 79, attached to the space station, fired its thrusters for 2 minutes and 41 seconds to lower the station's orbit. This action generated a safe margin of separation from a fragment tracked by ballistics specialists. The Expedition 66 crew aboard the station was not in any additional danger. [7]

16th June 2022: The ISS conducted a collision avoidance action to escape a large fragment (COSPAR ID[12]: 1982-92BYX, NORAD ID: 52590). This was the first time the risk of a collision exceeded the requirements for an avoidance maneuver. [8]

24th October 2022: The ISS conducted a second collision avoidance action for the year to avoid a potential high-risk collision with a large debris fragment (COSPAR ID: 1982-092BMN, NORAD ID: 51561). [9]

21st December 2022: The tracking data showed a close approach of a fragment of Russian Fregat-SB upper stage debris to the ISS. The consequential functionability action was the Roscosmos Progress 81 thrusters firing for 10 minutes and 21 seconds to avoid the estimated passing of the debris as closed as less than a half of kilometre from the station. This functionability action resulted in a postponement of the planned spacewalk by two NASA astronauts. [10]

6th March 2023: The ISS fired thrusters to avoid collision with an Earth observation satellite. The power came from the docked ISS re-supply ship Progress 83 and lasted just over six minutes slightly raising the station's orbit to avoid the approaching satellite. The new orbital trajectory did not impact the upcoming departure of the Crew-5 mission. [11]

14th March 2023: To provide extra distance from a fragment of Russian Cosmos 1408 satellite debris the ISS Progress 83 thrusters fired for a 2-minute and 35-seconds. NASA and Russian flight controllers worked together to conduct the maneuver to prevent the fragment potentially passing within 200 metres from the station. [12]

6th August 2023: The ISS taken PDAM to mitigate a projected high-risk conjunction with Cosmos 1408 debris (COSPAR ID: 1982-092BZV, NORAD ID: 52808). The 83P Progress vehicle thrusters were used to raise perigee altitudes by 0.73 km and 0.40 km, respectively. [13]

24th August 2023: Using the Zvezda Service Module's main engines as thrusters the ISS completed a PDAM to avoid a high-risk conjunction with Fengyun-1C[13] (FY-1C) debris (COSPAR ID: 1999-025DPV, NORAD ID: 35213). This action lowered the ISS apogee and perigee altitudes by 0.18 km and 1.34 km, respectively. Both the timing of the action and its retrograde direction were chosen to minimise the impact of the PDAM upon Progress 85P, the SpaceX Crew-7 vehicle, and the Soyuz 69S departure and 70S launch operations. [13]

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[11] Object 39915 was a piece of debris generated during the break-up of object 23106 (Pegasus R/B) that was launched on 19th May 1994. The rocket's upper stage break-up occurred on 3rd June 1996. [7]

[12] It was generated on 15 November 2021 as result of the antisatellite (ASAT) test on Cosmos 1408 by the Russian Federation. Since then, the ISS has experienced many conjunctions with its remaining tracked fragments.

[13] This debris was created by anti-satellite test on FY-1C conducted by the People's Republic of China in January 2007.

10th November 2023: The International Space Station (ISS) performed a Predetermined Debris Avoidance Maneuver (PDAM) at 15:07 GMT to mitigate a projected high risk conjunction with SL-16 debris (COSPAR ID: 1992-093KT, NORAD ID: 39841). This fragment was created during one of four known breakup events; the first event occurred on 26 December 1992, within 26 hours of the 25 December launch, and the last event occurring on 30 December 1992. The breakup parent was the Cosmos 2227 rocket body, a Zenit-2/SL-16 second stage. [14]

4.4 Summary of ISS avoiding actions

In summary during the 25 years of orbiting Earth the ISS has performed 38 functionability actions to preserve its safe operation. Annual and cumulative number of PDAMs executed thus far has been present in Figure 1.

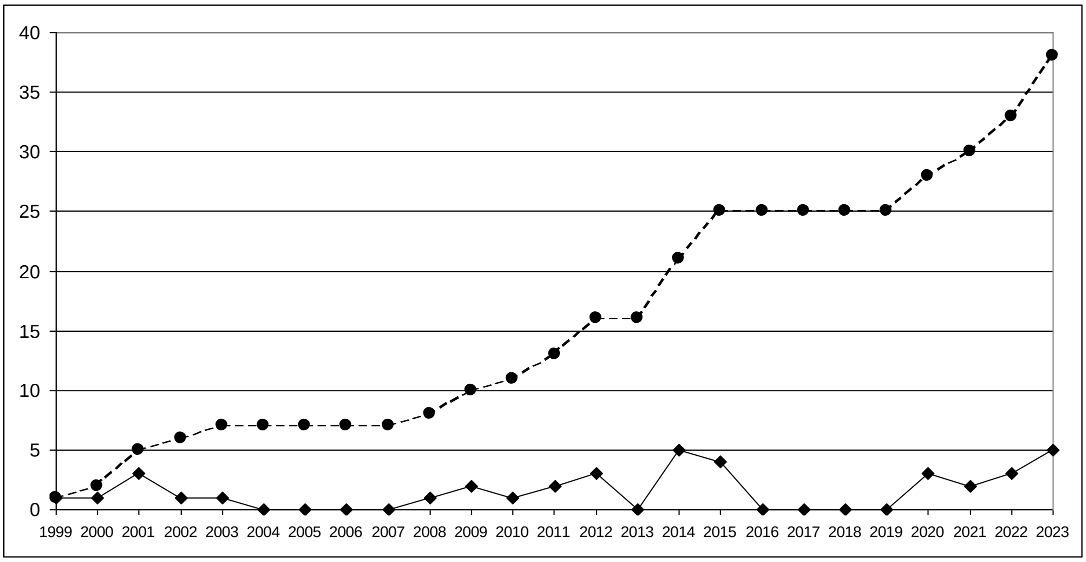

Figure 1. History of the ISS collision avoidance actions.

5. Resources used by Pre-Determined Debris Avoidance Maneuver PDAM

The NASA "Cost and Benefit Analysis of Orbital Debris Remediation" report about addressing orbital debris released on March 10, 2023 estimates the costs and complications of maneuvering the ISS in case of trouble. [15] Costs associated with pre-determined debris avoidance maneuver are briefly present below.

5.1 Risk Analysis Per Warning

Based on numerous public information sources, the report says that each maneuver requires two person-hours of risk analysis.

5.2 Labor per maneuver

That said, changing the ISS orbit would only be needed in a small minority of possible messages about "conjunctions" or close encounters with orbital debris (about 2%, the authors estimate with 100 person hours of effort charged at the standard labor rate).

5.3 Propellant per maneuver (cost of propellant).

Approximately 70 kg of propellant are required to boost the station and then another 70 kg would be required to lower it. Most PDAMs would also contribute to routine orbit-raising requirements that represent 90% of maneuvers with zero wasting propellant. Debris avoidance maneuvers that consumes propellant represent about 10%. To lower and then re-raise the ISS it would require 140 kg of propellant. Based on the cost of cargo being $70,000 per kilogram and that 10% of maneuvers consuming 140 kg of propellant, there is an average of 14 kg[14] of propellant used per maneuver making the cost per PDAM of one million dollars.

5.4 Lost work per maneuver (suspension of all activities of the ISS crew).

Suspension of all activities of the ISS crew during the orbital debris avoidance maneuver. The crew must be each time prepared for the potential immediate evacuation using Soyuz spacecraft. There may eventually be potential costs associated with interruption and potential cancellation of microgravity experiments.

5.5 Hardware cost of collision.

The above mentioned report assumes an impact would be from an object between 1 cm and 10 cm in diameter. The cost to repair such a debris puncture would be at least $200 million, as a spacecraft would need to go to the ISS bearing necessary materials for repair. However, the cost is likely much higher when taking into account numerous factors like crew time and lost science time, or potential repairs to non-core ISS elements like docked spaceships.

5.6 Lost operations due to collision.

The report indicates that a lost operations value per one ISS element out of service would be about $160 million per year. Given that there is no information how long the struck element would be in negative functionability state, it is assumed that the damaged ISS element would be minimum two years out of operations, leading to lost operations cost of about $300 million in total.

5.7 Contamination and mechanical erosion on exposed ISS surfaces by hypergolic components.

The bipropellant thrusters used by ISS (for reboost and attitude control) and other visiting spacecraft produce contamination and mechanical erosion on exposed surfaces which can impact optical properties and performance of systems such as the ISS solar arrays and robotic cameras, as well as introduce hazards to Extra-Vehicular Activity (EVA).
They are hypergolic components, either monomethylhydrazine (MMH) or unsymmetrical dimethylhydrazine (UDMH) as the fuel and nitrogen tetroxide (N_2O_4, or NTO) as the oxidizer. [16]

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[14] 0.9×0 [kg] + 0.1×140 [kg] = 14 kg

Table 1. Costs associated with debris avoidance.

Cost Element	Value	Cost
Risk Analysis	$200	Per Warning
Propellant	$1 million [a]	Per Maneuver
Labor	$8,000	Per Maneuver
Lost Work	$0	Per Maneuver
Lost Vehicles	$200 million [b]	Per Collision
Lost Operations	$300 million [b]	Per Collision
Contamination and Mechanical Erosion of ISS Surfaces	Unknown	Per Maneuver

[a.] Most maneuvers will not cause a waste of propellant, only a small portion. The average cost of waste propellant is presented.
[b.] Estimation for damage of single module, not the entire ISS.

6. Summary

MIRCE Science is a theory of the motion of working system through MIRCE Space caused by any action whatsoever. Consequently, the main objective of this paper was to present the pre-determined debris avoidance maneuvers of the International Space Station as a functionability action.

When predictions indicate that any tracked object will pass close enough for concern and the quality of the tracking data is deemed sufficiently accurate, a prudent functionability action for its avoidance is created by relevant mission control centres. The risk of each potential collision is calculated many hours in advance in accordance to the orbital elements of the debris object and potential target.

Calendar dates regarding 24 functionability actions have been identified and presented in paper of out 38 recorded. Identifications of the tractable orbital debris that constituted negative functionability actions threatening the safety of ISS are cited in accordance to the Committee on Space Research (COSPAR) of the International Science Council (ISC), (COSPAR ID) and North American Aerospace Defense Catalogue Number, (NORAD ID).

The paper clearly confirms the fourth axiom of MIRCE Science that states: The probability that a functionable (working) system type will move to a negative functionability state at any instant of time is greater than zero, regarding possible collisions of ISS with orbiting orbital debris. The randomness of occurrences of PDAM related functionability events during in-service life of ISS are presented in graphical form.

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