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Application of Artificial Intelligence in Solar System Exploration and Beyond

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Abstract: Carl Sagan's reflections emphasize the boundless potential awaiting humanity in space, regardless of our past achievements or failures. This optimistic view resonates with current space agencies, private space startups, and enthusiasts, all driven by the ambition to make humans a multiplanetary species. Key examples include Elon Musk's goal to terraform Mars, despite skepticism from some scientists. Space exploration faces numerous challenges, such as dealing with space debris, unpredictable climates on other planets, and the complexities of missions like NASA's attempts to land on Mars. Space missions confront obstacles in navigation, life detection, and sample testing. Astronauts also encounter physical and mental limitations due to the harsh conditions of space. Artificial Intelligence (AI) has emerged as a crucial tool in addressing these challenges. AI is categorized into supervised learning, unsupervised learning, and semi-supervised learning, with reinforcement learning being a distinct method used for autonomous applications. Neural networks, including convolutional and recurrent neural networks, mimic human behavior for tasks like image inspection and sequential data handling. Deep learning aids in complex pattern recognition, and natural language processing facilitates speech recognition and development. Expert systems enhance decision-making processes. This review explores various AI applications in space missions. AI technologies have been integral to recent missions such as the James Webb Space Telescope, which uses AI for object and galaxy inspection, and the ARTEMIS mission, which employs AI in designing new spacesuits. SpaceX leverages AI for reusable launch vehicles, while the European Space Agency (ESA) uses AI for autonomous spacecraft to cut mission costs. India plans to launch the AI-based Vyommitra robot in space and has utilized AI in the Chandrayaan mission for landing and navigation. Mars exploration benefits significantly from AI, given the planet's unpredictable weather and cratered surface. AI technologies, like the OASIS system, aid in mission planning and rover navigation. AI also supports space agriculture research, as demonstrated by the UAE's habitat design efforts. Beyond Mars, AI influences the exploration of asteroids and deep space. AI techniques, such as convolutional neural networks, assist in space dynamics calculations to predict asteroid trajectories and potential Earth impacts. AI has been employed in Voyager missions to seek extraterrestrial life and in the Hubble telescope for imaging exoplanets. AI enhances satellite communication and automates tasks on space stations, saving time and costs. Weather satellites, powered by AI, provide crucial alerts for natural disasters. Despite the challenges, AI offers promising solutions for advancing space exploration. The historical tendency to deem certain challenges insurmountable is gradually shifting, as past impossibilities, like human flight and space travel, have become historical milestones. This reinforces the importance of maintaining hope and persistence in the quest to explore space, as today's dreams may become tomorrow's history.

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1. Introduction

Space exploration has always been a frontier of human curiosity and ambition, driven by the quest to understand the universe and our place within it. Astrophysicist Carl Sagan's insights highlight the endless possibilities that lie ahead, encouraging us to keep pushing the boundaries of what we know and can achieve. Today, this spirit is embodied by space agencies, private companies, and enthusiasts who envision humanity as a multiplanetary species. However, the journey into space is fraught with challenges, from dealing with space debris and unpredictable planetary climates to ensuring the safety and effectiveness of missions. Amid these challenges, Artificial Intelligence (AI) has emerged as a transformative force, providing innovative solutions and new capabilities that propel space exploration forward. This review delves into the diverse AI technologies utilized in various space missions, illustrating how AI is not only overcoming current obstacles but also opening new horizons for the future of space exploration.

1.1. Role of AI in Autonomy of Space Vehicles

Autonomy in machines refers to their ability to make appropriate, independent, and logical decisions. This capability not only maximizes mission budgets but also enhances operational efficiency in orbit. The most autonomous spacecraft achieve level 4 autonomy, where human intervention is minimal. Artificial Intelligence (AI) enables astronauts to operate independently by incorporating human-like sentiments and decision-making abilities, known as strong AI. In contrast, weak AI focuses on solving specific problems. AI relies on storing and processing surrounding data to perform various tasks, including detecting potential failures in space missions.

1.2. Anomaly Detection in Spacecraft Using AI

For a spacecraft to achieve autonomy, it requires cognitive systems capable of detecting anomalies by perceiving both external and internal environments and deriving goal-oriented conclusions. Anomalies can be categorized into point anomalies, which occur when a single data point significantly differs from others; contextual anomalies, which require considering the point in relation to its neighbors; and collective anomalies, where groups of data points collectively deviate from expected system properties, even if individual points appear normal. Methods for identifying anomalies are classified based on their functional behaviors. Supervised methods involve training the system with data sets containing both normal and anomalous data, effectively handling known anomalies but potentially missing new ones. Conversely, unsupervised methods observe system patterns and label deviations from the norm as anomalies, offering broader detection capabilities without prior knowledge of specific anomalies. Thus, integrating cognitive systems into spacecraft enhances their autonomy, enabling effective identification and response to various types of anomalies.

1.3. Background of AI Used in Telescope and Space Missions

To identify system flaws, it is essential to thoroughly examine the technical aspects, evaluating each subsystem's performance and safety characteristics. This intricate process involves studying telescope flaws, a method employed by the European Space Agency (ESA) in their analysis of the Planck and Herschel telescopes. This analysis uses a specific algorithm to map data and transform it into simpler forms. The data is then categorized, distinguishing binary-based data from faulty data. Faults are identified, differentiated, and grouped, after which artificial intelligence techniques are applied for training.

Mapping the cosmic microwave background requires examining different microwave and infrared frequencies, a task performed by the Planck space telescope. Herschel, on the other hand, was used for infrared navigation. Both telescopes employed similar detection methods. The first method involved identifying errors and sending them to ground operators, maintaining the system in safe mode while anomalies were identified. The second method, the autonomous failure technique, allowed the spacecraft to detect irregularities independently, enhancing operational efficiency and safety.

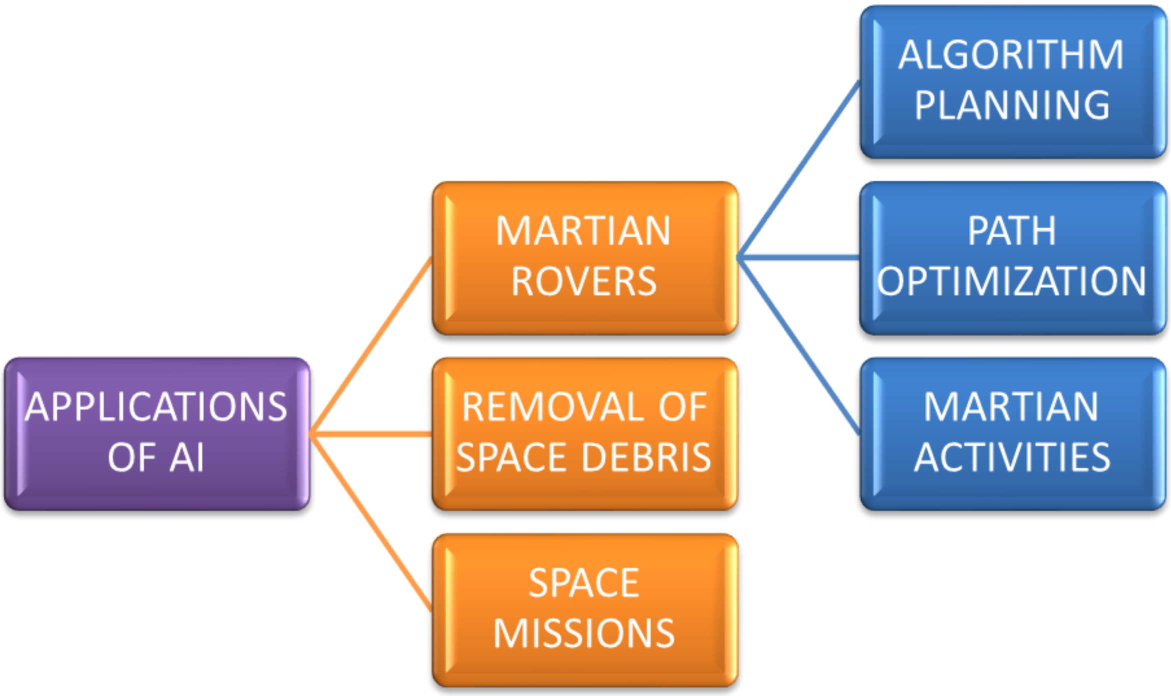

Figure-1 Applications of AI

2. Literature Review

2.1. Study of Oasis Martian Rover Algorithm

2.1.1. Planning Algorithm for Martian Rovers

Compared to their anticipated stay on Mars, the Martian rovers have survived many more days. To travel on Mars, take pictures, and identify dust samples, these rovers need a variety of autonomous systems. There is also a risk of wheel slippage due to the unknown conditions on Mars. To conduct long-range travel on Mars, we must develop precise plans that are controlled properly. Technology developed by OASIS supports this exploration. Rocks are photographed at high resolution and stored with their unique properties by the OASIS (Onboard Autonomous Science Investigation System) for data analysis. For the OASIS system to function, the CASPER system is necessary. Scheduling, planning, executing, and rearranging are continuous activities. The name Mars Exploration Rovers (MER) refers to these vehicles.

2.1.2. Path Optimization Algorithm for Martian Rovers

TDL assists in carrying out the quality plans that CASPER develops, acting as a middleman between the software's low-level commands and a variety of robotic actions. It brings various C++ language commands, such as creating constructors and managing exceptions. It also includes a linked architecture full of autonomous robotic technology called CLARAty. This method incorporates a measuring device that determines the precise location of the rover on Mars, addressing the problem of tracking the rover after a wheel slip. This system also explains newly found objects on Mars according to a specific process. First, it copies the previously captured information and stores it for protection. When additional communication occurs, the detected data is returned to Earth and flagged in the system.

Due to the unpredictability of geographic conditions, certain missions might be completed faster than anticipated, while others might take longer. To optimize our plans over time, new tasks can be added if the rover finishes its current task ahead of schedule. Conversely, if the rover takes longer than the allotted time, tasks are optimized by prioritizing the more crucial ones from the queue. Testing the samples discovered on Mars takes a long time. Thus, simulations were used to conduct the tests. These simulations were highly beneficial, maintaining the planning and mission duration. The hardware underwent the required physical testing using the six-wheeled FIDO undercarriage rover.

2.1.3. AI Algorithms for Martian Activities of Martian Rovers

Mars rovers have independent targets thanks to the self-governing exploration initiative. This technique also falls under OASIS. For automated decisions, it is utilized with the ChemCam installed on the rover. Prolific rovers with image identification systems, such as Perseverance, have also employed SuperCam formulas. Machine learning summary techniques made it easier to classify and analyze the craters found on Mars by the well-known Martian Reconnaissance Orbiter mission, saving scientists a great deal of time. The mission's intriguing goal was to find minerals within Mars's aqueous resources. The European Union, with its ambitious mission MARS EXPRESS, which uses autonomous thermal systems for its spacecraft, is also not lagging behind in the use of AI for space explorations. Two of its roles were to forecast the currents in each circuit and to maintain the system's components at the proper temperature, making it easier to calculate numerous electric properties. The excellent aspect of this system was its ability to identify the heat from the instruments and the spacecraft, saving energy for other uses.

Previously, scientists had specific types of images in mind and had to scroll through all the images. The problem was resolved by using scientific captioning techniques. By downloading only the images that scientists need, it saves them time. The planning software optimizes the rovers' paths to drive in the least possible time. Simulations are used to help with this in order to upload the optimal path. Solar panels will be mounted inside the futuristic rovers during construction, enabling solar power to charge them. Scientists have created an AI-based algorithm to determine the rovers' capacity when the sun isn't present at a given time. Mars experiences seasons just like Earth.

2.1.4. Overview of the Martian Atmosphere

The amount of oxygen fluctuates because the spring and summer seasons on Mars were so enjoyable for scientists. This led to the exploration of the oxygen-rich Martian environment. The oxygen proportion has been measured with the aid of spectrometers equipped with lasers. The procedure for determining the amounts of methane on the surface of Mars is the same. NASA has conducted numerous missions to observe the clouds in the Martian atmosphere. These clouds also showed patterns of methane and oxygen formation. Scientists believed that it would be possible to forecast Mars' aqueous cycle if the patterns of cloud formation were corrected. They construct models of Mars' clouds that resemble Earth's clouds for this reason.

2.2. Artificial Intelligence in Removal in Space Debris

2.2.1. Introduction to Application of Space Debris

The space age has motivated the next generation of explorers to go farther into space. A worldwide competition ensued among nations to launch their satellites and undertake missions aimed at studying the outer atmosphere. However, numerous components of these missions, as well as inoperative satellites and detached stages, lingered in space, contributing to the accumulation of space debris. Space debris should be controlled because it can impede the trajectory of our spacecraft and thus abort our space missions. AI applications have been used to solve this issue. Artificial Intelligence (AI) has the capability to offer algorithms that identify space debris and optimize the spacecraft's trajectory.

Space debris has the potential to destroy satellites and endanger our spacecraft. It could result in the creation of some permanent, pointless orbits. Tracking space debris using both earthly radar systems and telescopes is the simplest method for scientists to address this. While they are able to identify objects with small diameters, they are unable to identify minute components in lower Earth orbit. When restrictions on radar systems and telescopes arose, laser technology stepped in to help. By reacting to threats with timely updates, AI recognizes patterns in space debris. AI's ability to identify patterns allows us to distinguish between harmless space objects and hazardous debris. By integrating AI with certain sensors, debris traffic in space is managed. AI makes orbital calculations for us until the mission is finished, ensuring that spacecraft don't have to make maneuvers in response to debris.

2.2.2. Space Debris Removal Techniques of Space Agencies

Space debris tracking systems are being developed by NASA, the well-known space agency, using sensors on Earth and in space that are integrated with artificial intelligence. AI algorithms are utilized to analyze space debris, detect threats to missions, and find previously undiscovered hidden patterns. The ability to spot unique patterns makes these AI algorithms exceptional. Compared to earlier detection techniques, they can distinguish between different types of space debris and satellites. So far, the NASA system has identified numerous redundant satellites, leftover rocket parts, and detached stage components. The space industry was greatly encouraged by the AI solution to the problem of space debris. The challenge of space debris also inspired the European Space Agency (ESA). They applied AI by integrating it into satellites for debris detection, instead of using sensors. As far as space debris removal techniques go, ESA has emerged as a frontier.

2.3. Artificial Intelligence in Space Missions

2.3.1. Artificial Intelligence for Space Agencies in Space Missions

Many traditional philosophers argue that instead of investing in the aerospace industry, efforts should focus on finding ways to reduce poverty in the many impoverished nations around the world. However, the field of aerospace can significantly impact a nation's agricultural industry, forest area, conservation of energy resources, development of rural areas, and creation of more carefully planned urban areas. Satellite communication technology helps nations address each of these areas. Here, artificial intelligence is crucial between the satellites and the receivers. Satellites require AI assistance to capture the large number of images needed. AI examines every image and simplifies it for use in development. To preserve a nation's wealth and glory, natural disasters must be dealt with, and AI assists in informing the personnel on the ground about such events.

Experience from previous missions is crucial for the successful launch and completion of new space missions. It performs the role of a guide, advising scientists on how to properly carry out new missions. Space mission planning and analysis heavily rely on artificial intelligence. Semi-supervised models are the machine learning models used to design missions. There are several instances of AI being used in space exploration projects. For its Satellite-4, the Japanese space agency JAXA has also used AI to investigate the satellite's irregularities and manage its upkeep. Another well-known application of AI techniques is in analyzing the EgyptSat-1 failure detection system.

The medical and engineering fields are typically distinguished by young students. However, machine learning techniques serve as a mediator in this connection, made possible by the space sector. The space environment is unknown and occasionally unpredictable. The well-being of crew members is the main priority for manned missions. When astronauts are in harsh space conditions, their psychological support should be preserved. China has created nanosatellites to help astronauts accomplish this goal. These satellites are designed to fly autonomously in harsh environments like space. Tomorrow's space travel and space colonies will rely on artificial intelligence. Autonomous and IND are the best examples that bolster this.

2.3.2. Artificial Intelligence in Space Telescopes

For both navigation and moon landing, engineers are employing vision-based systems. Mars fascinates not only astronomers and astrophysicists but also the general public. Europa, the Saturnian rings, and numerous other space objects, including Jupiterian satellites, also captivate interest. One of the greatest successes of the twenty-first century is the launch of the James Webb Space Telescope into space. NASA conducted this mission to analyze the Hubble Space Telescope's discoveries and extend the Hubble Telescope's program duration. For the ground operators on Earth, it takes about twenty minutes to receive signals from the Mars rovers. It could take even longer for engineers to communicate with future missions, such as sending a spacecraft to Europa.

2.3.3. Artificial Intelligence in James Webb Space Telescope

Disc galaxies are susceptible to destruction by high redshift galaxies in motion. Using a Morpheus deep neural learning network, the present work analyzes data from various disc galaxies through the use of multiple artificial intelligence techniques. Disc galaxies during their early formation were not like the ones we see today. The ratio of rotational velocity to the dispersion of velocity in early-forming disc galaxies was lower, and the galaxies that exist today are the colder disc galaxies with more ordered rotation at the redshift dot. A smaller percentage of disc galaxies formed earlier, becoming aware of one another when this analysis was compared with the data from Hubble's observations. The findings of this work suggest that cold discs have existed in massive galaxies since the beginning of time.

A convolutional neural network based on model probability is called Morpheus. According to its prediction, pixel images could be categorized as compact/point source, irregular, disc, spheroid, or irregular. For every class, it generates a classification image based on the pixel sum. The CANDELS V1 EGS photometric redshift and stellar population synthesis analysis catalog were cross-matched with the data. Objects were chosen whose

Morpheus probability was greater than 0.5 and whose redshift was greater than 2. To match the NIRCam data with CANDELS, a mean astronomical detection was used. The results were found over more than 7,700 galaxies, of which approximately 1,600 were assigned to the disc galaxy category.

2.3.4. Artificial Intelligence in Recreating Image of a Black hole

The black holes in this research paper were trained using a primo algorithm. This algorithm was utilized to correlate information from various datasets in order to determine the image's resolution. The findings were utilized to estimate the mass of the central black hole of M87. They also provided the black hole image with characteristics such as width and a thinner and brighter ring. To create the ring-shaped images, a new algorithm called principal component interferometric modeling was employed. Principal analysis of the created simulations was the method employed, and the sampling of the linear combinations of the Fourier transforms was done using the Monte Carlo technique. In cases where there is no data, the Fourier transforms were filled using general imaging algorithms.

The image of a black hole was reconstructed using a simulation library containing over 30,000 images. For the reconstruction process, PRIMO employed N-1 parameters. One feature shared by all the black hole images was their common axis of spin, which was inclined at a 17-degree angle to the mean line. Here, N represents the total number of parameters used in the principal component analysis. The images were scaled using a dimensionless factor determined by the mass-to-distance ratio. To ensure that the dimensionality of the images remains unaffected by their size, a Butterworth filter was employed to blur the images.

3. Results and Discussions

3.1. Artificial Intelligence for Rediscovery of Newton's Gravitational Law (Result-1)

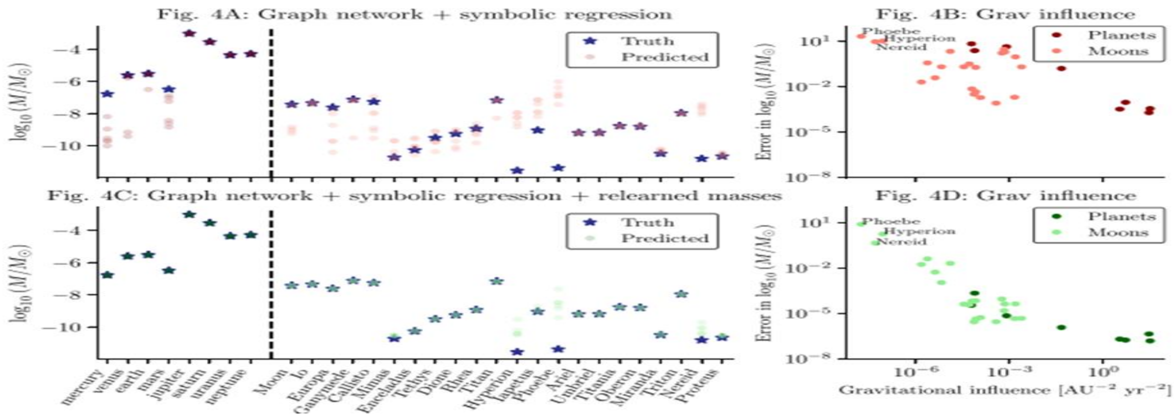

Figure-2 Comparison of Learned Scalars vk relative to the Sun [Image Courtesy: Pablo Lemos.et.al.2019]

Rediscovering Newton's Law of Gravitation and determining the masses of the orbital bodies were achieved through realistic observations of orbital trajectories. After their training, the simulators underwent regeneration. For each body, the model employed a single scalable scalar value. Newton's Second Law's force term F was divided by the scalar assumed to be a mass to determine the anticipated acceleration. For the learned simulator based on GN, a graph was provided as input (E, V). The term "V" grouped N-bodies together, while "E" represented the relationships between each pair. The model predicted the behaviors of the bodies having a value of the observed acceleration using the total system data. Since the model was trained to guess values for up to 30 minutes and due to the linearity of N-body dynamics, which produced minute anomalies, the predicted results were accurate for a few minutes before beginning to deviate. The upper-left corner of the results diagram displayed the learned scalar properties. According to the findings, there was a 9% error rate in the values between the scalar quantities that the model learned and the masses of the bodies.

3.2. Artificial Intelligence for Rediscovery of Newton's Gravitational Law (Result-2)

The symbolic regression method enabled the rediscovery of Newton's law of gravitation. The first six equations were ranked in decreasing order based on their highest scores out of 100 million. The equation that most closely resembled Newton's law of gravitation was represented by the largest rectangular shape in the outcome diagram. Errors and comparisons with actual data were displayed in the right panel of the diagram. When plotting the trajectories, the best-fitting equations and the experimental data source were taken into consideration. The orbits estimated by the symbolic expression exhibited extremely fine precision when compared to the trained simulators.

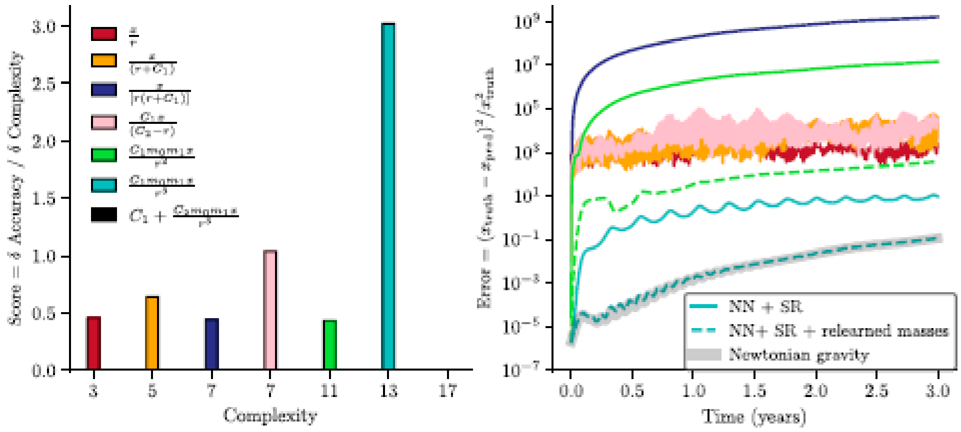

Figure-3 Newtonian Gravity Measurement [Pablos.et.al.2023]

3.3. Artificial Intelligence in Recreation of the Image of a Black Hole

Using PRIMO, an image was generated with a rim in the south and brightness in the middle. The interferometric visibility amplitudes were affected by the baseline length. Along with the Fourier transform of an image, this dependence took the shape of a Bessel function. In the case of an extremely thin ring, the diameter of the ring corresponded to the baseline length. PRIMO was employed to measure the diameter in 1750 steps. Observations revealed that the diameter obtained using the PRIMO algorithm closely matched the observed diameter of the black hole ring. Characterizing the accretion rate of a black hole depends on its ring width.

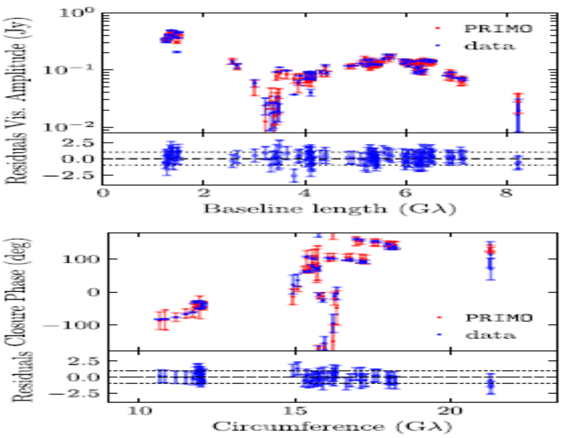

Figure-4 Comparative analysis between the amplitude of visibility (top) and the closure phase data (bottom) is conducted to determine the reconstruction of an image with a higher posterior. [Image Courtesy: Clarissa.et.al.2023]

3.4. Artificial Intelligence in James Webb Space Telescopes

An extended light distribution and a disk-like structure were observed in numerous galaxies, while others exhibited an amorphous light distribution and a greater central concentration. Observations of the galaxies indicated that 57% were classified as discs, and 21% had brightness values greater than a limit, i.e., H < 24.5 AB. However, only 5% of the 160 objects with brightness levels below 24.5 were identified as discs in the earlier HST model. For the remaining 49% of the total population of 202 objects, or 5%, the classification was previously given as spheroid in nature. The algorithm was unable to identify the remaining 20% of objects and ultimately classified them as background. Compared to the HST model, which found more than two, our JWST found only 202 galaxies out of the total population. It was found that forty percent of all galaxies had fewer than billions of solar masses of stars within them

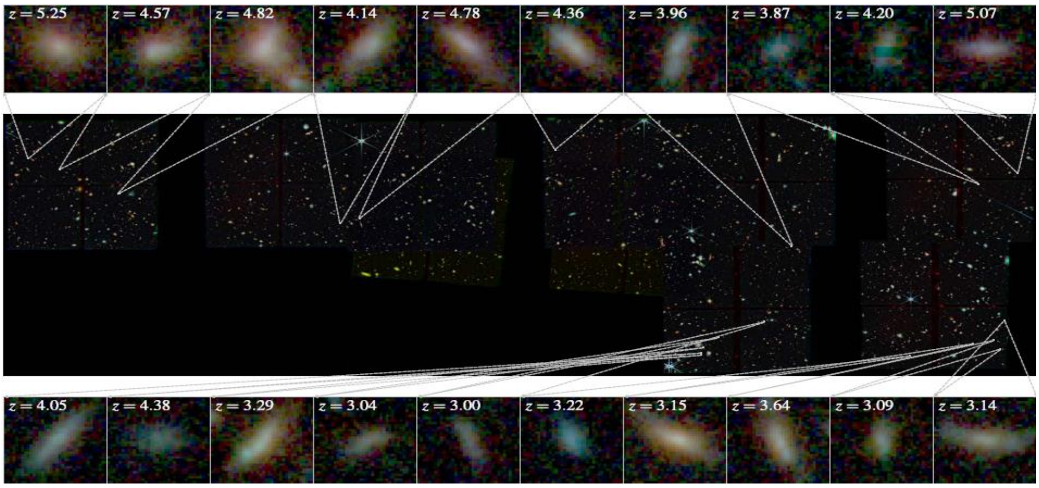

Figure-5 High-redshift disk galaxy candidates selected by the Morpheus AI/ML classifier in the CEERS EGS JWST imagery. The image displays a JWST F444W–F200W–F115W RGB false-color image in the center, surrounded by thumbnails of the 20 highest-redshift disk galaxy candidates arranged in the top and bottom rows. The majority of disk galaxy candidates selected by Morpheus exhibit flattened, extended light distributions consistent with disk morphologies.

3.5. Artificial Intelligence in Deviating the Trajectories of Hazardous Asteroids

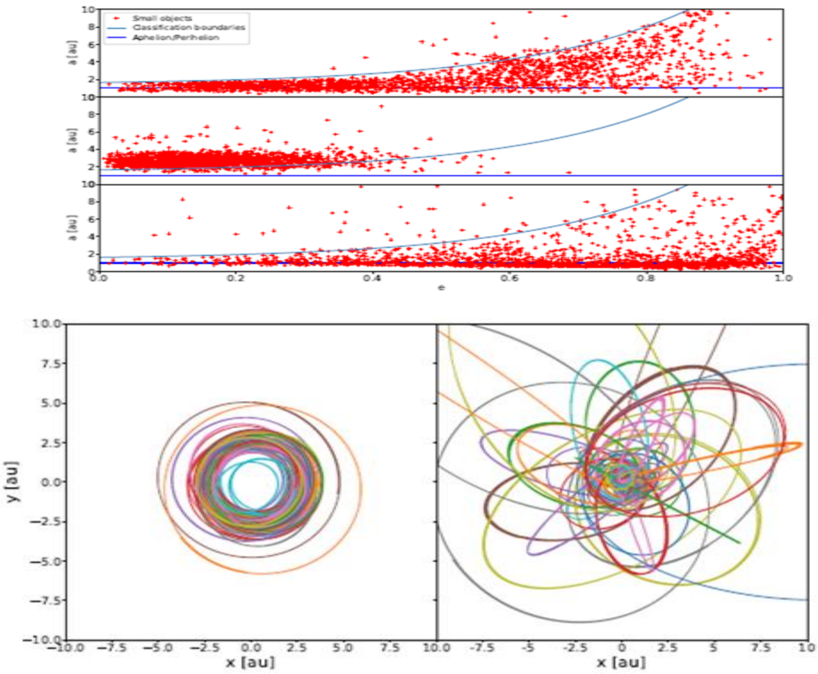

Figure-6 Illustration of trajectories between observed objects and Kuiper Belt Interlopers (KIs). The plot depicts the semi-major axis versus eccentricity for 2000 observed objects (PI, UO) and KIs. [Image Courtesy: John.et.al.2021]

Space missions may face threats not only from space debris but also from asteroids. Early discovery of asteroids can make our space missions easier to navigate. Applying artificial intelligence (AI) to the problem has enabled the calculation of the probability of asteroids striking by integrating their paths. This approach detected particularly dangerous asteroids for our missions by utilizing neural network techniques to assess the population of asteroids.The asteroid belt between Mars and Jupiter contains the greatest number of asteroids in our solar system, comprising up to 95% of them. The remaining asteroids are found in the Kuiper Belt, Trojan asteroids, comets, and satellites of other planets. Consequently, the asteroids outside the asteroid belt, constituting the remaining 5%, are relatively insignificant compared to those within the belt. According to the results, this method successfully detected nine out of ten known impacting objects identified by NASA. The AI and the trajectories of a hundred observed objects were examined. The orbits of the observed objects were highly elliptical, whereas those of the satellites launched were circular. The orbital plane for the observed objects was empty, while for the known impactors, it was densely populated. When the asteroids were combined, the network was able to select approximately 95% of the known impactors.

3.6. Artificial Intelligence in Spacesuits

For extra-vehicular activities in a spacesuit, this research paper serves as the foundation for the thermodynamic backpropagation model. The backpropagation model consists of three layers: input, hidden, and output layers. The input layer includes the heart rate, breathing frequency, and CO2 gas levels. The backpropagation neural network model determines human comfort level, metabolism, and cooling in spacesuits, while the output layer includes the metabolic rate and an output node. These dependencies are determined by the equation for heat balance. Conversely, the relationship between skin temperature and metabolic rate was measured at 0.30 ± 0.27, and the relationship between heart rate (HR) and metabolic rate was found to be up to 0.71 ± 0.53. The relationship between respiration frequency and metabolic rate was found to be 0.90 ± 0.05. Given the low dependency between skin temperature and metabolic rate, skin temperature was ignored, which could be attributed to the liquid water cooling suit. Increased muscle use and subsequent CO2 production are components of the metabolism process. The metabolic rate is determined by considering CO2 in this study.

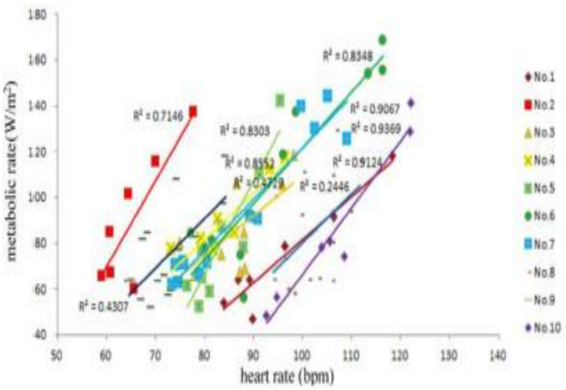

Figure-7 Heart-rate metabolic rate correlation

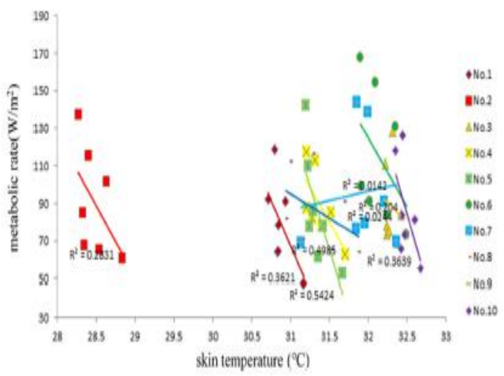

Figure-8 Skin temperature metabolic rate correlation

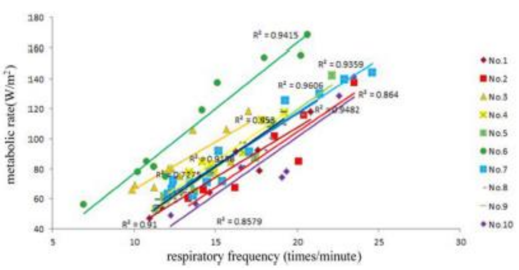

Figure-9 Respiratory frequency -metabolic rate correlation

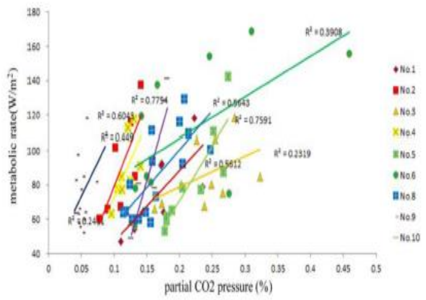

Figure-10 Partial CO2 pressure -metabolic rate correlation graph

4. Conclusion

Artificial intelligence has revolutionized many disciplines of science and technology, leading to the development of numerous research and techniques across various fields. However, the space sector is a newcomer to the application of artificial intelligence techniques and still faces many challenges. These issues can be addressed through the application of artificial intelligence. Space missions remain challenging unless they incorporate artificial intelligence techniques. These challenges include general space mission difficulties, as well as space debris removal and hazardous asteroid path detection.

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7. Conflict of Interest

The author declare no competing conflict of interest.

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