# Artifical Intelligence: New Paradigm in Deep Space Exploration

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***Abstract*—The unravelling mystery of deep space has led to the large investments made by several countries to employ various exploration schemes and strategies. Major organizations such as The National Aeronautics and Space Administration agency (NASA) have emphasized on the success rate of space exploration through the continuous development of space exploration activities, which in hand provides the full understanding of the solar system physical behavior to ensure Earth's sustainability. The employment of Artificial Intelligence techniques have had a crucial role to improve the ambiguous deep space exploration and to set strategies by 2030 for the possible exploration of Martian surfaces. In this review, a discussion based on two Artificial intelligence applications in deep exploration will be discussed – Hyperspectral Imagery systems & Robot systems in Space. Furthermore, Hyperspectral Imagery algorithm discusses the analysis of space image capture and analysis through various algorithms such as HERD and LEOPARD that are discussed in this review. Moreover, Autonomous robotic systems are also discussed in this review and its contribution to various deep space activities that contribute to efficient exploration. Finally, present challenges for employment of practical AI based deep space algorithms are discussed along with proposed solutions to ensure longevity in the future of deep space exploration.**

**Keywords— Deep Space Exploration, Artificial Intelligence, Image processing, celestial object identification, space mission scheduling**

## I. INTRODUCTION

Large investments made by numerous countries and global organizations have encouraged the development of space exploration strategies to target various solar systems around the global universe. Through various missions that involved robotics, approached discoveries took place in planet Mars, the moon and various meteorological surfaces [1]. The United states of America (USA) and the Union of Soviet Socialist Republics (USSR) were pre-dominant during the first era of space investigation, with numerous of space activities being evolved over time [2]. Various explorations launched by the United States paved the way to deep space exploration for the vast discovery to understand the physical activities of the solar system [3]. Since then, more than 150 deep space missions were launched in outer space by the top major countries and notable organizations such as The National Aeronautics and Space Administration agency (NASA) in the quest for successful space exploration. Furthermore, the rapid development of space exploration activities have established a long-term vision to attain a comprehensive understanding of the physical strength and science and develop technology substantially [4]. Promotion of scientific development would lead to the study of the possible consequential impacts in the solar system's orbital activity that could have devastating effects on the human environment. Therefore, deep exploration activities have been enhanced to provide sustainable and safety for the Earth and the human society [5], [6].

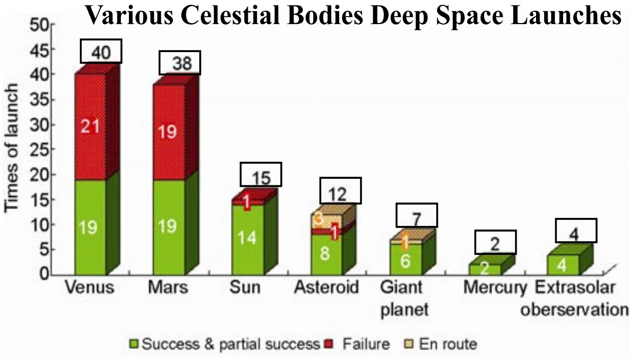


Fig. 1. Study of deep space exploration investigations for various solar system bodies [4].

Various objectives were set by the notable NASA organization as part of their vision for successful deep space exploration [7]. As illustrated in Fig. 2, the extended vision of expanding space exploration from surrounding Earth orbital and reaching the Mars orbit aims for the ambiguous deep space exploration and investigating the unknown environments within the Martian Surfaces.

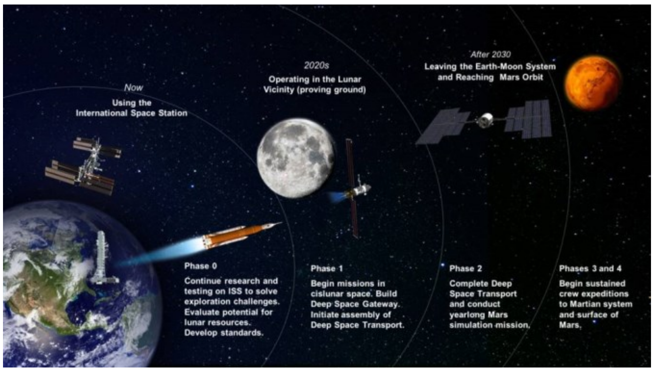


Fig. 2. Demonstration of Different Phases of deep space exploration in NASA's 2030 Vision [7].

The extensive development in deep space exploration, introduced the effective integration of artificial intelligence to constantly monitor the orbital environment with the complete dependence on human intervene for taking actions related to missionary tasks or detection of various celestial objects [8]. The integration of AI in deep space exploration dates back to the year 1998, through the implementation of the remote agent as illustrated in Fig. 3 [9]. Its main role is to detect any present failures in space activites and planning of space activities during space missions. This has further inspired the utilization of artificial intelligence in various detection mechanisms that require smart and efficient algorithms for the improvement of deep space exploration [10].

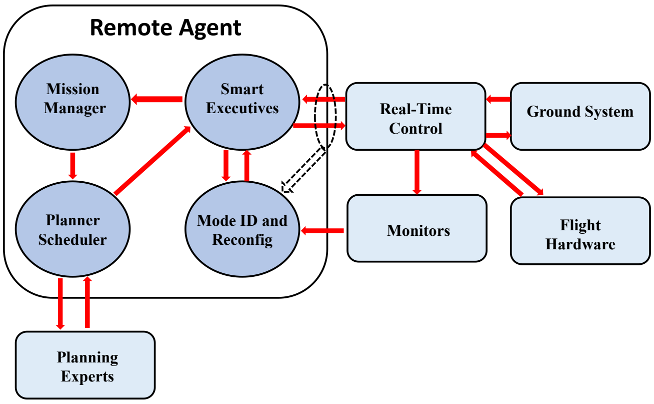


Fig. 3. NASA's implemented remote agent AI algorithm for space missions [9].

In this research, a review of selected important topics in deep space exploration will be discussed in complete detail. The implemented algorithms of such applications will be represented to gain a complete understanding of their employment in deep space exploration. Furthermore, the possible challenges of the algorithm implementation will be further discussed along with various proposed solutions. This study aims to provide an overview of selected artificial intelligence-based algorithms in enhanced deep space exploration.

## II. Overview of Artificial Intelligence Applications in Deep Space Exploration

### *A. Hyperspectral Imagery System for Deep Space Exploration*

The advancements in technologies enabled capturing, analyzing, and processing the images of different items at a very large number of wavelengths across the electromagnetic spectrum such as Hyperspectral imagery or Imaging spectrology. The recent advances in sensors and hyperspectral imaging system enabled high quality multidimensional data processing at very high spectral and spatial resolutions.

The purpose of hyperspectral imaging system is to collect the information as a set of images that consists of spectral information and represented by hundreds of spectral bands. As there are some reflected energies from the earth's surface invisible that are called infrared energies as illustrated in Fig.4 [11]. The developed hyperspectral imagery system collects the entire spectrum of the reflected energy to be processed and analyzed later.

The importance and the benefit of such system is using this advanced technology in space exploration and specifically in satellite hyperspectral remote sensing for earth observation application. Collecting valuable hyperspectral images from the space means acquisition of data that consists of a good perceivable feature such as sharpness and color contrast. Hyperspectral imagery has several applications in space exploration such as detecting different types of materials, which have reflectance spectra features such as minerals mapping detection and specifying different soil properties, for instance: soil moisture, salinity and organic content [12]. Moreover, hyperspectral imagery has been successfully applied and used in specifying the vegetation species and it has numerous other applications in object detection and classification.

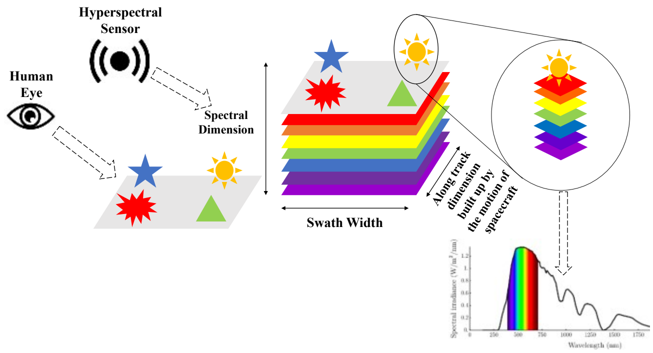


Fig. 4. Identification of materials through a continiuous spectrum

The Multispectral image data is processed with the following steps:

1. Reviewing the input data: In this step, general information about the dataset is gained such as its size, quality, and the general characteristics of the collected data.
2. Defining the class of data: Defining the class/type of material to specify the classes of data to be discriminated or to be carried out. This step is usually performed and implemented through training the system on a set of sampled data. Then analysing the data becomes an extrapolation from these training samples to the entire data set.
3. Feature extraction: In this step, the required features to be identified or calculated must be extracted to be valid and available for some computation or calculation processes.
4. Analysis: In this step, specific algorithms are running to analyse the input dataset to consider and process the desired data and discriminate the others.
5. Evaluating the result of the analysis: In this step, the quality of the result will be evaluated by quantitative and qualitative methods.

There are several image analysis algorithms and methods that were developed to analyse the information and multispectral data collected by the hyperspectral imagery system. Artificial intelligence had played a crucial role in developing the most accurate algorithm used for analysing and classifying the images in hyperspectral remote sensing that is Deep Machine Learning, where the classification framework was developed based on Deep convolution Neural Network and support vector machine, which is able to provide high-level spectral-spatial constructed features automatically without the need to send the huge collected information and captured images to the ground to be interpreted or analysed by human.

The deep convolution neural network is a developed effective method used for feature extraction and object classification. The hyperspectral data along with hundreds of spectral bands and channels can be difficult for the human to distinguish between them, thus the deep convolutional network is able to perform the classification of the objects with a very high performance.

There are several hyperspectral imaging sensors that have been developed for space flight which was built by TRW (Space Based Hyperspectral Imagery of the Moon and Earth Limb) which developed the NASA sponsored Lewis satellite and the Hyperian sensor.

In addtion, there are many companies that aimed to propose AI-based space products such as KP LABS in Poland, which have developed various AI solutions to apply autonomy in space domains, such as space robotics LEOPARD and HERD.

The Herd is an AI based algorithm that was designed to facilitate the process of analysing the data of earth observation [13]. It includes three main elements:

1. Pre-processing of the data: this element enables misalignment correction, bad pixel masking, optical distortion correction, georeferencing and sensor-level radiometric corrections.
2. Spatial resolution enhancement of images: this element is designed for single and multiple image super resolution reconstruction, machine learning and deep learning.
3. Data analysis: This element is critical to analyse the data through dimensionality reduction, feature extraction, classification, segmentation and so on.

The Herd algorithm was designed to be used on earth and in the on-board satellite. Moreover, as it consists of the required elements for the earth observation process, it supports the optical data acquisition through data preparation and data classification, segmentation, compression and many more features, which makes it able to handle high dimensional data, hyperspectral and multispectral images.

The elements of this advanced algorithm designed to be fitted in FPGA processor, and it is also compatible with the Xilinx-based on data processing units.

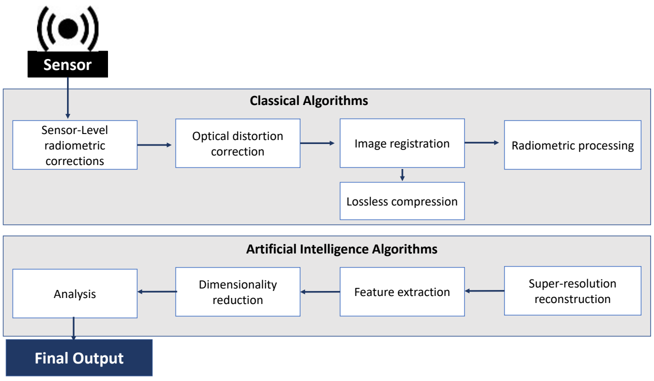


Fig. 5. The Processing Diagram of the Herd Algorithm [13]

Another important AI-based solution for on-board data processing is LEOPARD which is a data processing unit that enables managing and processing of data in orbit. It was built using Deep Neural Networks to process the huge data in orbit and sending the valuable data and its results to the ground stations, which led to reducing the time and cost of the huge data transfer to let the ground stations focus on any new detected phenomena [14].

Leopard is provided with a field programmable gate array (FPGA) to manage the execution process of deep learning and machine learning algorithms to have a throughput up to 3 Tera Operations per second.

Leopard has some technical specifications that are further demonstrated in Table 1. The specifications of Leopard data unit are provided with a 150-bank hyperspectral sensor to preform image segmentation and object detection.

TABLE I. TECHNICAL SPECIFICATIONS FOR LEOPARD DATA PROCESSING UNIT

| | |
|---|---|
| **Processing Cores** | Quad ARM Crtex-A53 CPU up to 1.5 GHz<br>Dual ARM Cortex-R5 in lockstep<br>FPGA for custom function implementation |
| **Memory** | 4-16 GiB DDR4 with ECC<br>4-16 GiB SLC flash-based file system storage.<br>Up to 2x256 GiB SLC flash-based data storage. |
| **Interfaces** | Interface: CAN , SPI, UART, GTY transceivers, Ethernet, Space Wire, LVDS and Rs422/485 interfaces. |
| **Specifications** | Supply voltage: 6.5 to 14 V<br>Power consumption: 7.5 W to 40 W<br>Computational Throughput for Neural Networks: up to 4 TOPS<br>Thermal interface for satellite architecture<br>A radiation hardened payload controller |
| **Software Ecosystem** | 64-bit Linux<br>Deep Learning Accelerator<br>Fully reconfigurable in orbit |

## B. *Artifical Intelligence Robots in Space*

Generally, robots were used in many different applications and aspects including industry, education, transportation, entertainment, etc. Moreover, with the help of the advanced technologies and techniques in Artificial intelligence and Machine learning.

There are a variety of robot types and application that were implemented outside the earth's surface, where the robots also were used in space exploration.

Robots with artificial intelligence techniques were deployed in many space applications such as:

Earth observation: it is one of the areas that artificial intelligence and machine learning are being used extensively. Robots with AI techniques were deployed in the space to monitor some areas like dangerous and hazardous environments. Artificial intelligence solutions were implemented in the satellite orbital operations and the communication between these satellites, which are observing and collecting data about the earth's surface and artificial intelligence robots that are receiving the collected data to perform some analysis operations to process the data or take a specific action.

Autonomous Navigation: autonomous robots and satellites can help in navigating different places and areas like areas of deforestation. As the autonomous navigation system is provided with a unique capability and features , which is built with on-board software to perform the navigation process successfully. Such software systems that are built with image processing, intelligent algorithms, and manoeuvre computations to execute all the required functions efficiently.

Planetary Exploration: Robotics with advanced artificial intelligence allows the curiosity of humans to explore the different plants in many ways such as the soil, rocks, and other conditions.

These technologies help in exploring planets, moon, and asteroids efficiently and in a cost-effective way by collecting data about the objects that can't be accessed by humans and it helps the scientists to discover several minerals, and some resources like water in the hazardous environments. Furthermore, Nasa developed an advanced system specially to identify “Hazards in Electromagnetic Fields" without sending humans into risk and dangerous environment.

Moreover, Nasa has developed AI-based space robot assistant called Robonaut which was designed to assist astronauts to perform their job successfully throughout their journey in the space, which allowed them to focus and discover other new aspects [15].

The Robonaut is a humanoid robot which was produced in the year 2000, but engineers in NASA continued working on improving the robot with many versions and upgrades, where Robonaut is able to “Think” by itself and take decisions and provided with a remote controller to be controlled form the stations.

Fig. 6. Robonaut during a round testing of the first humanoid robot in space [15].

## III. Present Challenges

Artificial intelligence, machine learning and the advancement in technologies had a transformative impact on space exploration. Although, the crucial role of artificial intelligence in producing such technologies and techniques to facilitate the space exploration process, but the implementation of such technologies is involved with many challenges. This section illustrates two types of challenges that are technical challenges and environmental challenges

### *A. Technical Challenges*

The technical issues and challenges are a main part in developing any system, where the technical issues can be either from the software or the hardware part. In order to develop an intelligent system that can work efficiently in space is not an easy task. So, the developers must make sure about every detail in the Hardware components and connections. Moreover, they must think about the unexpected errors and how to maintain these errors in space, especially in case of an autonomous robot, spacecraft, and satellite, which might let them think about working and developing a maintenance system or providing a backup system for the unexpected situations for the fully automated or intelligent system in the case of human being absence.

Implementing intelligent systems in space requires specific capabilities, as the system should have the ability to work in uncertain environment and handle noisy data collected from different sensors. As a result, the system should be provided with automated learning and computer visions techniques and trained effectively through deep neural networks algorithm, which require a great deal of computational resources that provides high complexity on board. Therefore, another challenge of implementing AI-based solutions on board is the cost, where some methods such as **current vision-based terrain modelling** are inherently computationally expensive, where these methods are required for performing complex tasks and analysis on a large input set and searching for the best and optimal choice through large sets of data to make a decision [16].

### *B. Enviornmental Challenges*

One of the biggest challenges for intelligent systems is interacting with the on-board environment that is totally different from the environmental testing conditions the system was designed, developed, and tested in. Additionally, where one of the main reasons to develop the intelligent systems is to explore the space instead of humans, is saving humans from the risk of performing some operations or unexpected situations that might happen on board. The complexity of performing some operations in space is characterized by high degree of uncertainty that might result from interacting with the on board environment such as navigation, observation, drilling, coring, sampling, ...etc. For instance, during the traverse operation, the craft may consume energy more than the expected. Therefore, instead of direct human interaction, we are in the need for intelligent systems to monitor the progress and the performance of the operations and take the optimal decision where the delays in the communication with earth is being increased accordingly [16].

In addition to the challenges of interacting with the space environment , testing the intelligent systems on earth where it has been proven that the gravity gets lower and weak in space. That is why Nasa developed "Zero Gravity Research facility" in 1996, which is the largest facility of its kind in the world that simulates a weightless environment of the space.

It is used by Nasa to test the impact of microgravity on different physical phenomena and demonstrate its impact on developing new technologies and test the developed or proposed hardware designs or spacecrafts to flight abroad, where this facility is one of the solutions to overcome the environment challenge [17].

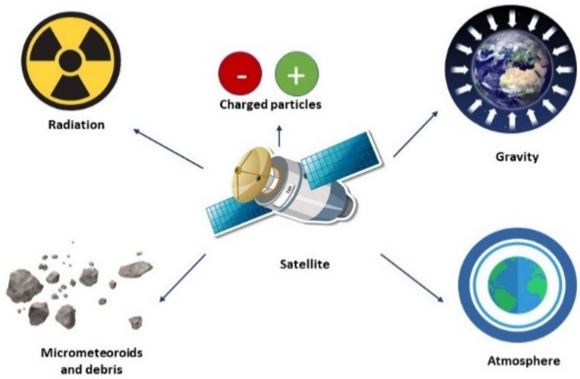


Fig. 7. Environmental factors affecting spacecraft in space

## Conclusion

The advancement of artificial intelligence technologies and techniques in space exploration have led to a dramatic breakthrough in space exploration and processing data on-board.

The advantages of the artificial intelligence techniques facilitate the space environmental mapping and exploration as they make main contributions in optical remote sensing, observing the earth, moon and other planets. Although intelligent systems and robots are being used for scientific purpose in space for collecting data, processing and analysis data on-board, they also possess new non-scientific jobs like maintenance of spacecrafts, constructions, prospecting, etc...

Moreover, the primary goal of implementing intelligent systems and robotics in space is to explore and obtain scientific data and information about the space, avoiding the astronauts in risk exposure of exploring new environments, reduce the human effort and workload as the world needs to invest these efforts in conducting depth research and experimentation based on the analysis and the processed data from the intelligent systems, hyperspectral imagery system and other advanced technologies, which make the intelligent systems and robots an integral part of the space exploration process.

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