Harnessing AI for the Future of Space Science and Technology

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Abstract - Artificial intelligence (AI) is rapidly transforming the future of space exploration by enabling autonomy, precision, and efficiency in missions beyond Earth. International Space Research organizations', includes NASA (USA), ESA(Europe), Roscosmos (Russia), ISRO(India), JAXA(Japan), and CSA(Canada), have integrated AI technologies into critical projects that mark milestones in human spaceflight and robotic exploration. From NASA's Perseverance Rover employing autonomous navigation on Mars and ESA's Rosetta mission using AI guided descent on a comet, AI has been Central to planetary exploration. ISRO's Chandrayaan-3 demonstrated hazard detection through AI assisted landing near the lunar South pole, while JAXA's Hayabusa-2 and SLIM missions employed mission learning for asteroid sampling and pinpoint lunar landings. On the international Space station (ISS), a joint platform of NASA, Roscosmos, ESA, JAXA, and CSA, AI-driven systems is such as ESA's CIMON chatbot and robotic assistants support astronauts in real time problem solving and Research tasks. AI algorithms, including Simultaneous Localisation and Mapping (SLAM), convolutional neural networks (CNNs), Reinforcement Learning (RL), Kalman filters, and Bayesian models, are being applied for navigation, health monitoring, planetary mapping, anomaly detection, and data analysis. These advancements not only enhance the efficiency of space missions but also reduce dependency on earth based decision making, which is critical for future long duration missions to the moon, Mars, and beyond. Collectively, the collaboration of leading international agencies in developing AI enabled system underscores the role of artificial intelligence as a cornerstone of next generation space research.

Keywords: Artificial intelligence, Space Exploration, Perseverance Rover, Rosetta Comet mission, Chandrayaan-3, Hayabusa 2, Canadarm2 and Dextre, Autonomous navigation.

I. INTRODUCTION

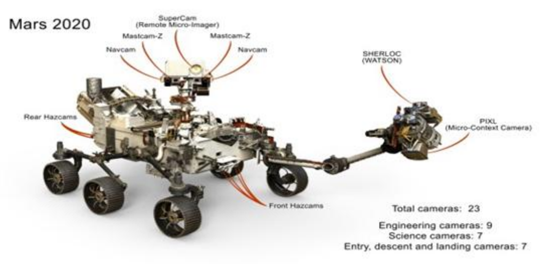
To evaluate the role of Artificial Intelligence (AI) in global space exploration, this study looks at the agencies have gradually integrated AI into their missions to improve spacecraft autonomy, enhance navigation and landing accuracy, process large astronomical datasets, and support astronauts on the International Space Station and the range of AI's impact, its visible role in major missions and its quiet but vital role in operational efficiency and scientific discovery.

II. METHODOLOGY

- NASA (National Aeronautics and Space Administration, USA) AI Application:

Perseverance Rover (Mars, 2021–present)

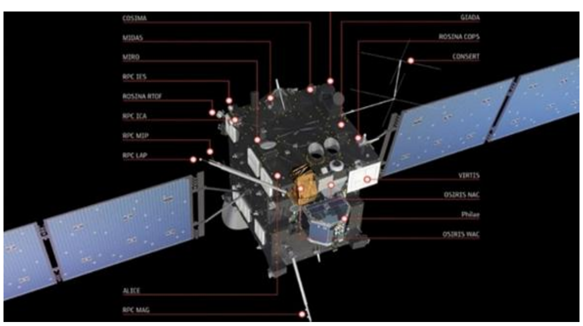
The NASA Perseverance rover uses several AI applications for scientific exploration. One of these is the Autonomous Exploration for Gathering Increased Science (AEGIS) software uses computer vision and feature recognition, which lets the rover autonomously target and zap rocks with its SuperCam laser. It also has adaptive sampling software that uses the rover's (planetary instrument for x-ray lithochemistry) PIXL instrument uses Machine learning and pattern recognition to analyze and choose minerals of interest in Martian rocks for future collection. SLAM (Simultaneous Localization and Mapping) builds a map of the Martian terrain while determining the rover's exact position in real time. Reinforcement Learning helps the rover learn optimal driving strategies through trial-and-error to navigate safely and efficiently. Kalman Filter fuses data from multiple sensors to accurately estimate the rover's position and movement on uneven terrain. AI also powers the rover's autonomous driving features. This ability allows it to map terrain and navigate around obstacles,



making it more efficient and better at exploring unknown areas.

- ESA (European Space Agency) AI Application: Rosetta / Philae Comet Mission (2014)

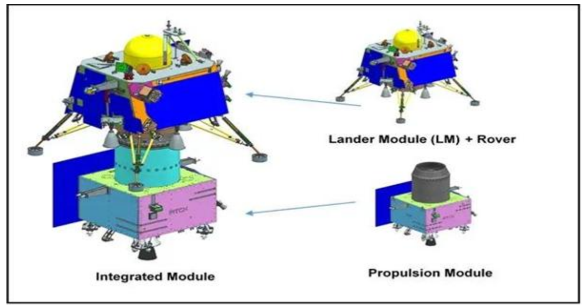
The European Space Agency's Rosetta/Philae mission used artificial intelligence (AI) primarily for automated scientific planning and scheduling. The mission's JPL ASPEN/RSSC (Automated Scheduling and Planning Environment, Remote Agent Scheduling System Component) system helped in the process of long-term, medium-term, and short-term planning by determining valid observation intervals, even when constraints ruled out specific times, making the planning more efficient and allowing for manual analysis of results. Autonomous Navigation use image processing, star tracking, and Kalman filtering so that Rosetta orbiter's autonomous navigation systems had to work perfectly to maintain the spacecraft's position and orientation relative to the comet during its orbits.



- ISRO (Indian Space Research Organization) AI Application:

Chandrayaan-3 Lunar Mission

The Hazard Detection and Avoidance Camera (HAC) works with AI-driven software that uses computer vision and machine learning algorithms to process terrain images in real time. The most common software frameworks used are based on Convolutional Neural Networks (CNNs), Simultaneous Localization and Mapping (SLAM), Reinforcement learning improves autonomous decision-making and Machine Learning Algorithms – Used broadly with CNNs and other models to classify terrain features and hazards for adaptive navigation.



- JAXA (Japan Aerospace Exploration Agency) AI Application:

Hayabusa2 Asteroid Mission (Ryugu, 2014-2020)

Hayabusa2 did not use modern deep learning AI packages like TensorFlow or PyTorch because these are not certified for flight and can be too unpredictable for critical missions. Instead, it relied on AI-inspired autonomous software integrated into its Guidance, Navigation, and Control (GNC) system. This software included algorithms such as, Computer vision algorithms for detecting target markers using thresholding and centroid extraction. Kalman filters for combining data from the camera, laser altimeter, and star tracker. Autonomous decision-making rules in the Guidance Sequence Program for selecting descent, abort, or landing steps. Control algorithms like proportional-derivative and sliding-mode controllers for firing thrusters.

- CSA (Canadian Space Agency) AI Application:

Canadarm2 & Dextre (on the ISS)

Canadarm2 and Dextre, created by the Canadian Space Agency, use robotic AI software combined with machine learning and control programs to support operations on the International Space Station and it uses forward kinematics algorithm. Canadarm2 uses AI-assisted movement and planning systems, along with computer vision tracking, to automatically align and capture spacecraft, move heavy payloads, and help astronauts during spacewalks. It relies on safety measures and control systems to ensure precision in microgravity. Dextre, known as the robotic "handyman," uses similar AI software but is improved with reinforcement learning and fine-motion control programs. This enables it to carry out sensitive tasks such as handling tools, replacing small parts, or refueling satellites.

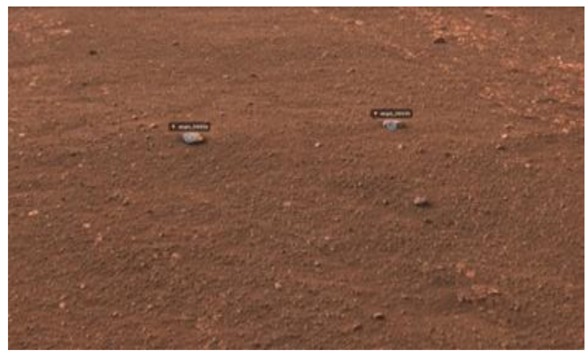
Together, the software and systems allow Canadarm2 and Dextre to operate semi-autonomously, lightening the workload for astronauts while making space station maintenance and spacecraft servicing more reliable and efficient.

III. RESULTS AND DISCUSSION

- Perseverance Rover

Perseverance's main goals are to find evidence of past microbial life, analyze Martian rocks, and store samples that may later be brought back to Earth.

AEGIS is a target selection software powered by AI. It helps the rover make its own decisions about which rocks or surface features are interesting and should be studied. This addresses the issue of long communication delays between Mars and Earth. AEGIS uses images taken by the rover's Mastcam-Z or other imaging tools to assess the shape, texture, and color of rocks. It identifies possible targets that might hold useful geological or chemical information. By linking PIXL with AEGIS, the rover can prioritize and analyze rocks in real time without waiting for instructions from mission control. Intelligent software guides precise scientific instruments to conduct autonomous research on another planet. This approach overcomes communication delays and operational limits, allowing the rover to make informed decisions in real time as it searches for clues about Mars' geological history and its potential to have supported life.



This shows a view from a distance of the each of the two rocks that AEGIS targeted. This image was taken from software used by the Perseverance team to select science targets.

Rosetta / Philae Comet Mission:

The European Space Agency's (ESA) Rosetta–Philae comet mission was used to study Comet 67P/Churyumov–Gerasimenko up close to learn more about the origins of comets and the early Solar System. The Rosetta orbiter observed and mapped the comet from space, while the Philae lander touched down on the comet's surface to analyze its composition, structure, and gases, helping scientists understand how water and organic molecules may have been delivered to Earth billions of years ago.

To tackle this, ESA used the ASPEN (Automated Planning and Scheduling for Space Exploration) AI tool, which was originally developed by NASA's Jet Propulsion Laboratory (JPL).

ASPEN used a constructive, priority-based algorithm to create schedules that followed

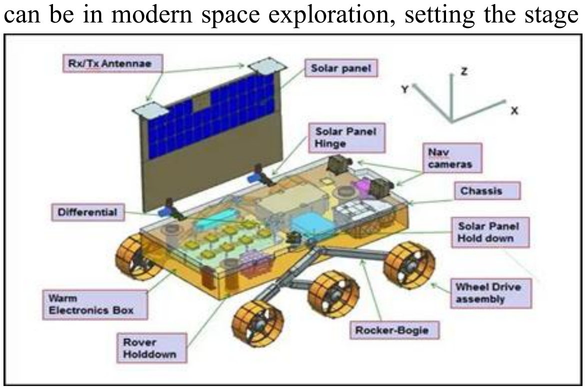
Philae Landed on Comet

different restrictions, like instrument capabilities, spacecraft orientation, and power availability. A major use of ASPEN in the Rosetta mission happened during the Medium Term Planning (MTP) phases, which lasted about four weeks. For example, in MTP 6, ASPEN helped schedule over 2,100 observations across 58 science campaigns. The tool was particularly useful during critical times, like when deploying the Philae lander, as it helped manage multiple contingencies and last-minute planning needs. ASPEN use, showed how effective AI-driven tools can be in modern space exploration, setting the stage

for future missions that need similar precision and coordination.

- Chandrayaan-3 Lunar Mission :

Chandrayaan-3 aims to explore the Moon's surface. It focuses on safely landing and operating a rover in the lunar south pole region. Studying the lunar surface and terrain. Examining soil and rocks to understand the Moon's makeup. Demonstrating self-guided landing technologies using AI for hazard detection and navigation. Helping future lunar exploration missions by testing landing and mobility systems.



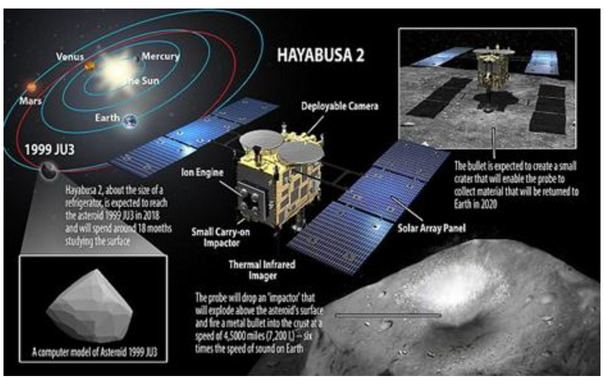
The Hazard Detection and Avoidance Camera (HAC) played a key role in the lander Vikram's autonomous navigation system. It worked with onboard AI software to ensure a safe landing on the moon. The HAC took high-resolution images of the lunar surface during the final descent, and these images were processed using computer vision algorithms in the lander's guidance system. The AI software mainly used CNNs for real-time image recognition to differentiate between smooth landing areas and dangerous features like craters, boulders, or slopes. In addition to CNNs, feature-matching algorithms such as ORB (Oriented FAST and Rotated BRIEF) and optical flow techniques tracked the spacecraft's movement and position over the terrain.

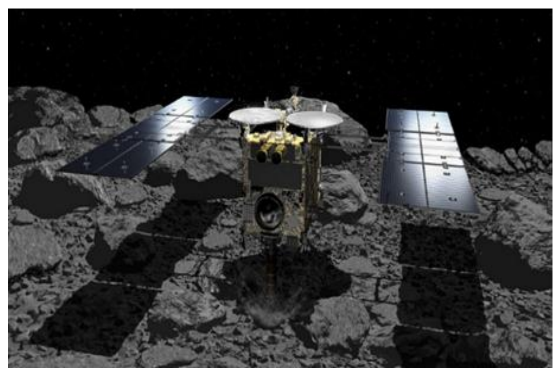
To achieve autonomy, Chandrayaan-3's landing software also used Simultaneous Localization and Mapping (SLAM) concepts. This allowed the system to create a continuous map of the lunar surface from HAC data while locating the lander within that map. The map was then cross-verified with preloaded lunar surface maps from orbiter data. The AI-driven hazard detection module recognized unsafe areas in real time and sent this information to the Guidance, Navigation, and Control (GNC) system, which recalculated and adjusted the descent path within seconds. Also, reinforcement learning models were trained in simulations before the mission,

helping the AI choose safer descent routes based on previous lunar landing experiences.By integrating the HAC hardware with AI software, Chandrayaan-3 achieved a completely autonomous soft landing near the lunar south pole on August 23, 2023. The system successfully identified hazards and guided the lander to a flat, safe surface without needing help from ground control. This overcame the challenges that caused the Chandrayaan-2 lander to crash. The combination of AI, CNNs, SLAM, and real-time vision algorithms with HAC made Chandrayaan-3's landing one of the most accurate and dependable lunar descents in space exploration history.

- Hayabusa2 Asteroid Mission :

Hayabusa2 is a Japanese space mission created by JAXA (Japan Aerospace Exploration Agency) to study the asteroid Ryugu and bring samples back to Earth. Hayabusa2 gave scientists important insights into organic materials and water that may have played a role in forming planets and life on Earth.The Hayabusa2 mission successfully navigated and sampled an asteroid using a set of AI-driven algorithms integrated into its onboard Guidance, Navigation, and Control (GNC) system. While it was near asteroid Ryugu, the spacecraft employed its Optical Navigation Camera (ONC) to take pictures of the asteroid's surface and the reflective Target Markers (TMs) it had deployed. It processed these images with traditional computer vision techniques that included noise filtering, thresholding, and centroid extraction to highlight the marker's bright reflection against the uneven landscape.





To maintain precise positioning, the spacecraft combined this visual data with distance measurements from the LIDAR altimeter and attitude information from star trackers. It then used a Kalman filter to combine the data and keep a steady estimate of its location and speed in real time. This estimate contributed to the autonomous decision-making process, which was managed by a rule-based AI program known as the Guidance Sequence Program (GSP). This program determined whether to continue the descent, pause for verification, or abort the mission if any hazards were detected. After confirming a safe descent path, the system activated control algorithms, including proportional-derivative (PD) controllers and robust sliding-mode control, to produce thruster commands. These commands stabilized the probe and enabled millimeter-level accuracy during landing.

Hayabusa2's "AI" was not a single software product. It consisted of a collection of onboard autonomous algorithms that enabled it to navigate, select landing zones, detect hazards, and collect asteroid samples without relying on commands from Earth.

- Canadarm2 & Dextre :

Canadarm2 and Dextre are robotic systems created by the Canadian Space Agency to help with operations on the International Space Station (ISS). These systems rely on complex robotic AI software with multiple layers of algorithms to achieve precision, autonomy, and adaptability in microgravity.

Canadarm2 is a large robotic arm that captures and docks spacecraft, moves heavy equipment, and helps astronauts during spacewalks. Dextre, often known as the "robotic handyman," is a smaller, more precise robot designed for delicate tasks such as replacing small parts, refueling satellites, and performing maintenance that would otherwise need human astronauts.

Together, they use AI-powered control and vision systems to carry out complex, semi-autonomous tasks. This reduces the workload for astronauts and makes maintenance on the space station safer and more efficient. The software framework combines robotic operating systems, sensor fusion modules, and real-time control structures. This setup allows the robots to see, plan, and act in an ever-changing environment. Canadarm2 is a 17-meter robotic arm that can move large payloads. It uses inverse and forward kinematics algorithms to determine joint angles and paths. This capability enables accurate positioning of cargo, modules, and even helps astronauts during spacewalks. Its AI includes trajectory optimization, collision avoidance, and computer vision algorithms. These processes use data from onboard cameras and sensors to adjust movements instantly, ensuring efficiency and safety.

Dextre, on the other hand, is a two-armed robot designed for delicate tasks. It depends on reinforcement learning algorithms, rule-based expert systems, and high-precision motion planning algorithms to handle sensitive jobs like swapping instruments, refueling satellites, and performing maintenance tasks that might be risky for astronauts. Dextre's AI features force-feedback control, tactile sensing, and sensor fusion. This allows it to sense the surroundings, detect resistance, and make tiny adjustments on its own, increasing reliability and minimizing the need for human input. This collaboration leads to semi-autonomous operation, precise manipulation, and real-time decision-making. In turn, this boosts efficiency, safety, and mission success on the ISS.

IV. CONCLUSION

The space missions Perseverance Rover, Rosetta, Chandrayaan-3, Hayabusa 2, and Canadarm2/Dextre show how artificial intelligence (AI) and autonomous technologies have become crucial tools in modern space exploration. AI enables these spacecraft and robotic systems to operate on their own in extreme and unpredictable environments. Human involvement is often limited by communication delays, distance, or dangerous conditions. The integration of AI in space technology is opening doors for the next generation of robotic explorers and interplanetary missions that can perform complex tasks independently. This lays the groundwork for sustained human and robotic presence beyond Earth.

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