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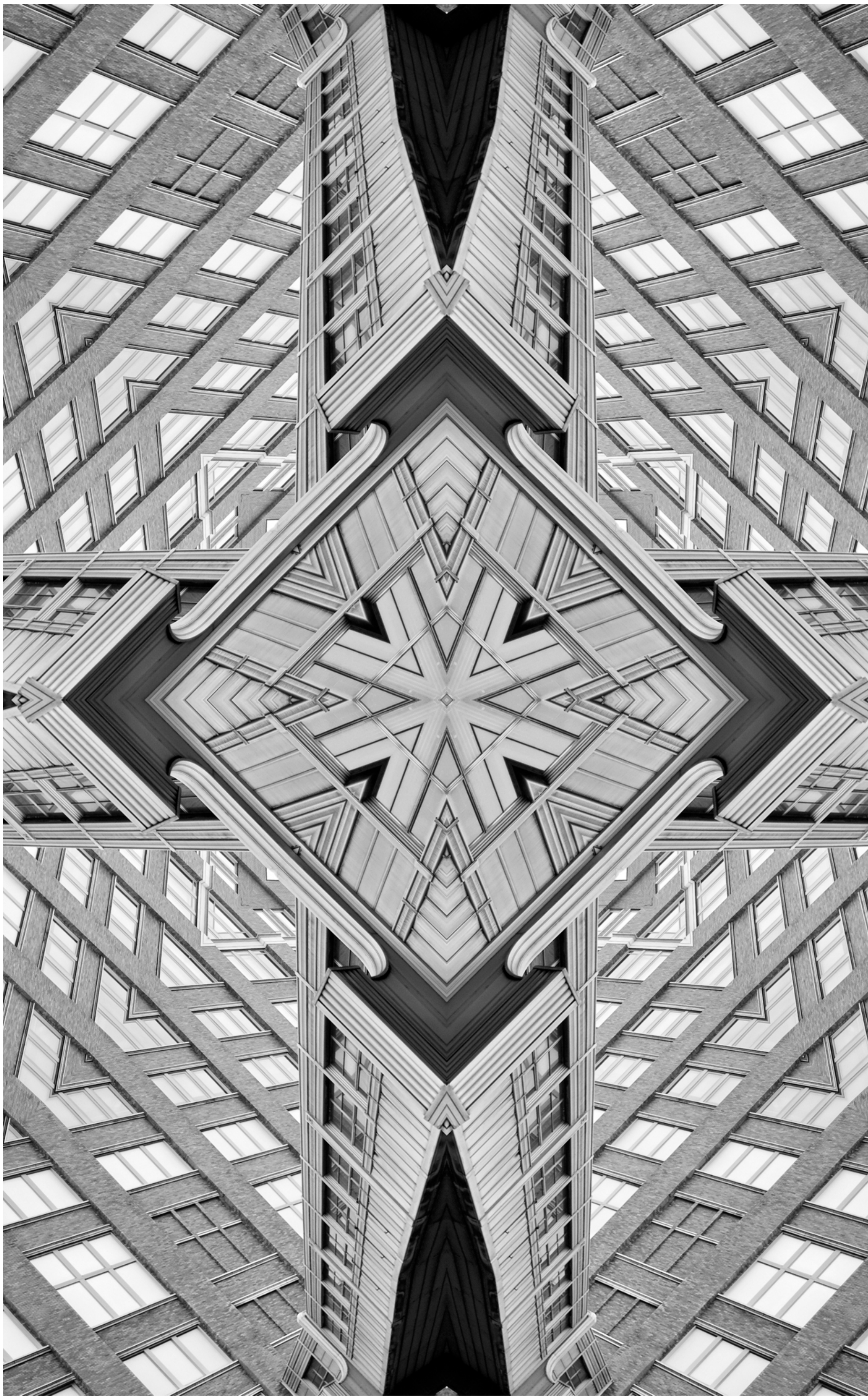

AI in Space Operations: Opportunities and Challenges

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Abstract

As AI technologies evolve, they hold immense potential for transforming space operations. However, there are significant challenges for both Earth-based and onboard AI, including cybersecurity threats, supply chain vulnerabilities, and the complexity of operating in extreme environments. Given the sector's strategic nature, the national security implications of these challenges make it imperative that India adopts a comprehensive approach to AI development in space. It must leverage its own strengths as well as strategic collaborations with trusted partners to balance innovation with security. This brief examines how key spacefaring countries are integrating AI into their space operations, identifies their strengths and areas of development, and charts a way forward for India's AI-driven space ambitions.

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Introduction

In the new golden age of space exploration, Artificial Intelligence (AI) is pushing the boundaries of human capabilities even further than previously imagined possible—by revolutionising space operations, from planning and automation to launch and communication. As the sector goes through a period of exponential growth, AI will be a key to unlocking the full potential of space exploration and creating breakthroughs for anticipated commercial ventures such as space tourism.

India has acknowledged the importance of this niche. The Indian Space Research Organisation's (ISRO) Respond Basket 2023[a] included eight research areas focused on AI and Machine Learning (ML).[1] It has also launched initiatives like the 'AI for Space and Geospatial Innovation: ISRO Immersion Startup Challenge' in 2024, that is aimed at fostering the development of AI applications in space.[2]

However, like in any other sector, AI in space is fraught with challenges and uncertainties. Given the sector's strategic nature, these threats are posed not just to the operations but to national security, overall. India can learn from and partner with other spacefaring nations to address these challenges while driving innovation in its domestic ecosystem. This brief examines how key countries are deploying AI in space operations, the challenges they face, and their strengths and areas of development. It outlines a path for the future of AI in space.

a ISRO's Respond Basket comprises the most urgent and important research problems identified by ISRO/ DOS Centre/ Units based on ISRO's upcoming programmatic R&D requirements.

Applications and Risks of AI in Space

AI applications for space operations can be broadly categorised as either Earth-based or onboard.

1. Earth-based AI covers activities such as predictive models for mission planning, resource allocation, trajectory optimisation, and data analysis from satellites and Earth-based instruments. Japanese astronomers have used AI to remove noise[b] from astronomical data, accurately mapping the shape of galaxies.[3] Digital twins[c] and other AI solutions are also being developed to increase the cyber resilience of space systems.[4]

2. Onboard AI comprises systems deployed on spacecraft to reduce reliance on ground control. Autonomous spacecraft and rovers use AI for navigation and decision-making. In the US, the National Aeronautics and Space Administration (NASA) is using AI to train Mars rovers to autonomously seek minerals based on real-time data.[5] Machine Learning solutions are also being explored for on-orbit servicing, assembly, and manufacturing.[6] AI will also play a key role in the identification of weapons in space,[7] and advancing robotics, virtual assistants, and crew support for human missions.

Applications like communication optimisation and debris tracking through space situational awareness can be deployed from either or both platforms.[8,9] However, onboard AI in space faces unique environmental challenges, making its deployment complex. These systems must contend with radiation and extreme temperature variations. Additionally, AI systems consume massive computational and power resources. AI devices often require high currents at low voltages, which is hard to achieve in space. Both the software and hardware need modification to operate in extreme conditions,[10] slowing the development of onboard AI despite numerous promising use cases.

Irrespective of the AI system's location, data quality and training remain key concerns. However, the nascent and strategic nature of both the technology and operational domains poses cumulative national security risks.

1. **Cybersecurity**: AI systems used in space operations face the threat of cyberattacks that could disrupt communications, manipulate algorithms, and compromise sensitive data or control over key infrastructure.[11] If the

b Noise is the random contribution from other sources that affects the measurement of a signal.

c A digital twin is a virtual representation of a real-world system that is used for real-time monitoring, simulation, testing, and maintenance.

model data is corrupted, it could lead the system to make flawed decisions, potentially resulting in strategic disadvantages.[12]

2. **Components**: Both space and AI systems rely on specialised components sourced from multiple countries. With highly sensitive systems, there is concern that manufacturing nations may introduce backdoors[13] or malware,[14] compromising security and functionality. Overdependence on foreign suppliers also creates supply chain vulnerabilities for the importer.

3. **Tampering**: Hardware and software tampering during manufacturing or before deployment is another notable risk. Malicious firmware or hardware that allows adversaries to disrupt the AI system is particularly challenging in space, where physical access to the spacecraft is limited once deployed.[15,16]

The following section discusses how key players in space are developing their AI ecosystems to enhance operations, along with their unique strengths and challenges in development and deployment.

India

Initiatives

India has ambitious plans for AI in space. In addition to the Respond Basket and ISRO Immersion Startup Challenge, India has already deployed AI for space missions and exploration. The Pragyan rover and Vikram lander in Chandrayaan-2, launched in 2019, and Chandrayaan-3, launched in 2023, were AI-equipped to facilitate landing and navigation on the lunar surface.[17,18]

For the Gaganyaan mission, India's maiden human space mission, which is tentatively scheduled for late 2026, ISRO will launch an AI-enabled half-humanoid, Vyommitra, into space. This robot will test the Geosynchronous Satellite Launch Vehicle Mark III (GSLV Mk III) rocket and ensure its safety for human travel, tracking changes in the crew module during spaceflight and return.[19]

The Indian private sector is also integrating AI into its operations. For instance, Dhruva Space uses AI and ML for onboard processing to minimise the need for downlinking large datasets. Edge computing improves operational efficiency by conducting initial data analyses in orbit.[20]

Strengths

- **Enabling Ecosystem:** The Government of India launched the IndiaAI mission in 2024 to create a comprehensive AI system in the country. The plan aims to build AI computing infrastructure, create datasets, develop indigenous models, generate financing, and foster innovation across sectors.[21] The government's enthusiasm to create a conducive environment is a strong sign of progress for AI development in India.

- **Cost-Effective Innovation:** India has built a reputation for cost-efficient advancements in space technology.[22,23] The integration of AI in missions like Chandrayaan-2 and Chandrayaan-3 further demonstrates its capability to leverage AI while keeping costs low.

- **IT and Software Industry Expertise:** India's robust IT and software industry provides a strong foundation for developing AI technologies. Bangalore, the country's IT hub, has also become a centre for space technology. With a large pool of skilled engineers, India is well-positioned for the rapid development and deployment of AI in space.

Advanced Space Hardware Capabilities: ISRO has well-developed capabilities in designing and developing space-qualified parts such as Application-Specific Integrated Circuits (ASIC),[24] and Field Programmable Gate Arrays (FPGAs).[25] These can be adapted for AI-driven space systems. The onboard processing capabilities of Indian satellites further strengthen India's position for future advancements.[26]

Areas of Development

- **Resource Constraints:** While resource allocation has improved in recent years, India's space programme is still not as well-funded as global missions.[27] In 2024, India's Department of Space was allocated INR13,042.75 crores (approximately US$1.57 billion),[28] compared to NASA's US$24.875 billion budget. AI systems in space require substantial investments, which are constrained by India's broader economic limitations. The country's focus on cost-effective solutions is often driven by necessity, but increased access to resources could unlock the full potential of India's capabilities.[29]

- **Data Processing Capabilities**: India's AI development is hindered by limited computing infrastructure, representing less than 2 percent of the global total.[30] In contrast, the US and China control nearly 60 percent. Bridging this gap is a challenge for India's ongoing AI development across AI industries.[31]

Initiatives

China has been purposefully leveraging AI in space for both civilian and military applications. Researchers have claimed to conduct groundbreaking experiments, including temporarily giving AI full control of a satellite to test its decision-making.[32] China's commercial Earth observation satellites, such as the Jilin-1, are equipped with AI to improve the precision tracking of small objects. Satellites launched by China in recent years feature processors capable of uploading; the latest AI algorithms to automatically identify and track moving targets in real time without ground assistance.[33] China has also conducted experiments with using AI in space combat, training an anti-satellite AI to command three small "hunter" satellites to trick and capture a target in a simulated space battle.[34]

China plans to continue expanding its constellation of AI-enabled satellites. Chang Guang Satellite Technology, which operates the Jilin-1 satellite constellation, aims to grow it to 300 satellites by 2025.[35]

Strengths

- **Strong Government Support and Strategic Vision:** The Chinese government has a strategic approach to AI, actively making concerted efforts to develop the domestic ecosystem. Substantial investments in research and development have propelled China into an AI leader.[36] Following the US's Wolf Amendment, passed in 2011, which banned NASA from scientific cooperation with China, Beijing intensified efforts to build its own systems with a focus on space security.[37]

- **Military-Civil Fusion (MCF)**: China's MCF approach has helped drive AI development exponentially. The Artificial Intelligence Development Plan, announced in July 2017, identified MCF as one of the six main duties for AI development.[38] The PLA's active pursuit and funding of AI have provided a boost for the ecosystem as a whole.

Areas of Development

- **Dependence on Foreign Technology:** Despite its advancements, China still relies on other countries, especially the US, for critical technology components in its AI and space systems. This makes it extremely vulnerable to supply chain disruptions, sanctions, and trade restrictions. Since 2022, the US imposed export controls blocking China's access to advanced AI chips made using US inputs.[39] In January 2025, Chinese AI firm DeepSeek, released an open-source large language model (LLM), DeepSeek-R1. Its cost, efficiency, and capabilities challenged perceptions of China trailing in the AI race and raised questions about the effectiveness of the export controls. However, export controls have a time lag and the compute gap that China faces will be a growing concern as deployment increases.[40]

- **Lack of Self-Sufficiency:** China's generative AI initiatives are reliant on Meta Platforms' Llama system due to the absence of indigenous alternatives.[41] Additionally, there is a shortage of quality Chinese-language data online, as most of this data tends to be either state media or spam websites, which create very low-quality and potentially problematic datasets.[42]

United States

Initiatives

The US leads in both AI and space, maintaining a minor edge over China in output quality despite China's rapid development.[43] The US has been innovating across sectors such as space exploration, satellite management, and debris tracking. The Perseverance rover, for instance, uses a computer vision system called AEGIS to detect and classify rocks on Mars.[44] Stanford's Center for AEroSpace Autonomy Research is developing AI projects that combine trajectory optimisation with generative AI to enable autonomous space flight.[45] NASA's Europa Lander mission prototype[46] plans to leverage autonomy to reduce ground-in-the-loop (GITL) cycles, preserving mission time and energy. The mission's harsh environment and communication delays necessitate autonomous decision-making and in-situ data analysis. AI will help these missions to prioritise tasks, manage resources, and make real-time scientific discoveries without direct human intervention. The US also prioritises military applications, as reflected in its Data and Artificial Intelligence Strategic Action Plan, that emphasises the importance of modernity and agility in its data and AI systems.[47]

Strengths

- **Technological Leadership:** The US leads globally in AI technology,[48] driven by advanced research institutions like NASA and tech companies. Its extensive and diverse AI deployments in space highlight its capacity for innovation and integration of cutting-edge technology.

- **Robust Private Sector and Funding:** The US benefits from a vibrant private space sector, with companies like SpaceX, Blue Origin, and many AI startups contributing to advancements. This dynamism has raised venture capital funding to its highest point in recent years.[49]

Areas of Development

- **Adversarial Threats:** The US's competitive position against Russia and China has raised concerns about potential adversarial attacks.[50] China's rapid development in AI increases the risk of sophisticated attacks on critical space assets.

- **Developing Low-Cost AI:** The US has long viewed AI development as capital-intensive, relying on massive investment for breakthroughs. DeepSeek's low-cost approach upended this assumption, causing panic in American markets. To avoid appearing less resource-efficient and innovative than China, the US must quickly adapt to this alternative trajectory.

Japan

Initiatives

Japan was an early adopter of AI in space, with the Japan Aerospace Exploration Agency (JAXA) using it for the launch of Epsilon in 2013. AI reduced the number of people needed at the launch centre through by serving as self-inspecting function.[51] Japan also use AI to handle the enormous volumes of data collected by its telescopes. The Subaru Telescope, operated by the National Astronomical Observatory of Japan (NAOJ), used AI in its 2014 "Galaxy Cruise" project. The initiative used citizen science to train AI to classify galaxy morphologies with 97.5 percent accuracy. Mitsubishi Heavy Industries developed AIRIS (Artificial Intelligence Retraining in Space), that can sift through Earth-observation data to identify dark ships[d] and reduce delays in launching interventions.[52]

Strengths

- **Automation and Robotics Expertise:** Japan is globally recognised for its expertise in robotics, successfully integrating advanced AI-driven robots into space missions, including those used in lunar missions.

- **Strong Research and Development Ecosystem:** Japan has a robust research and development ecosystem for space launch systems,[53] involving collaborations between JAXA, academic institutions, and private companies.

Areas of Development

- **Ageing Workforce:** Japan's demographic challenges, including an ageing workforce, pose difficulties in maintaining a steady pipeline of skilled professionals in AI and space technologies.

- **Absence of a Private Sector:** Japan's space sector lacks strong private participation, remaining 90 percent dependent on government.[54] The limited domestic market prevents economies of scale.

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d Dark ships are vessels that switch off their Automatic Identification System to avoid detection while carrying out illegal activities.

Initiatives

South Korea, with decades of space operations behind it, established the Korea Aerospace Administration in 2024 to coordinate and further expand its space activities. Its long-term goals include landing a robotic spacecraft on the Moon by 2032 and a Mars mission by 2045,[55] both involving significant AI integration for navigation, data collection, and autonomous decision-making. South Korea aims to become a key player in the global space industry with ambitious future plans.

Strengths

- **Concerted National Efforts:** The South Korean government has released several policies to bolster AI development, including the 'National Strategy for Artificial Intelligence' in 2019[56] and the 'Plan to Strengthen the Competitiveness of Hyper-scale AI' in 2023.[57] These plans aim to create a favourable regulatory environment, cultivate talent, and create infrastructure clusters to accelerate the growth of the AI industry.

- **Strong Semiconductor Industry:** South Korea is a global leader in semiconductor manufacturing, crucial for space technologies, particularly in AI and data processing.[58] Its expertise in chip production provides an advantage in developing advanced AI systems for space applications, such as satellite technology and autonomous spacecrafts.

Areas of Development

- **Limited Domestic Market:** Private companies in South Korea struggled to create new markets and form a self-sustaining space industry ecosystem, resulting in a lag in technological advancement.[59]

- **Lack of Funding**: The Korea Aerospace Research Institute lacks adequate government funding. In 2015, the lunar module project exceeded the institute's annual budget. Larger projects consume the majority of the budget and manpower, leaving other missions underfunded or ignored.[60]

The Way Forward for AI in Space

The use of AI in space will continue to grow. Earth-based systems are widely used for scientific, military, and developmental endeavours. As human space missions increase and new commercial ventures such as space tourism develop, onboard AI will become crucial for space missions. AI will automate mundane tasks, improve decision-making, counter cybersecurity threats,[61] and improve biomonitoring and Earth-independent healthcare.[62] Additionally, as spacecraft advance to traverse greater distances, AI-enabled communication and data transfer will be vital.

AI systems must be developed to be more transparent to build confidence and more robust to handle faults and unexpected situations without human intervention. The development of transparent, fault-tolerant AI systems will be a key challenge to overcome.

Extensive testing of systems and components is essential to detect anomalies and tampering, requiring the development of diagnostic tools that can keep pace with evolving malicious technologies. Strengthening physical and cybersecurity measures across manufacturing, transportation, and deployment phases is also essential. Developing these solutions involves transnational cooperation.

The paralysis of multilateral organisations has highlighted the need for India to invest in and leverage bilateral and minilateral relationships to further its strategic interests.[63] These choices must be based on the opportunities and drawbacks of potential partner countries.

India's relationship with China has been tense since the Galwan Valley clash in 2020. Despite the potential for a tactical thaw,[64] the military standoff continues, and India remains wary of Chinese technology.[65] Japan and the US also have strategic interests that conflict with China. However, despite shared reservations, these countries have more AI investment activity with China than with each other.[66] This disjointedness between interests and actions must be remedied for safe and trusted technological development. India can collaborate with global leaders in space exploration and AI, prioritising scientific and economic development without compromising its national security interests.

The US and India share strong private-sector ties, driven by substantial US funding in India's space ecosystem. India has taken this a step further by allowing 100 percent foreign direct investment (FDI) in the space sector.[67]

The Way Forward for AI in Space

Going forward, India should build on its space situational awareness agreement with the US[68] beyond military data sharing and acquire access to large datasets required for training AI models, such as satellite imagery, environmental data, and mission telemetry.

Japan's ageing population has prioritised innovation in advanced automation and robotics,[69] offering India an opportunity to absorb and contribute to these advancements. Japan can bridge manpower gaps in its technology ecosystem by outsourcing human resource-heavy stages of AI development to India. As Indian ministries and governments adopt space technologies,[70] India also offers a larger market for the Japanese private space sector to grow.

South Korea excels in semiconductor technology—a key component of the compute infrastructure India aims to develop. It has reinforced its ambitions with a recent US$19 billion investment in its chip industry.[71] This presents a key area for India-South Korea collaboration. Collaborative efforts could involve the development of specialised space-AI chips that account for factors like radiation resistance, power efficiency, and reliability. India, contributing 20 percent of the global chip design talent,[72] can strengthen its role by developing a domestic ecosystem that generates Indian-owned patents. Combined with its AI software expertise, India can help optimise these chips for space missions.

International debates on sharing and managing space data have[73] direct national security implications. Ethical issues, such as equity and inclusion in space access, will also contribute to the discourse and direction of policy. There is a need for widely accepted technical standards that permit interoperability, safety, and transparency in space. Countries must balance protecting sensitive data with enabling scientific collaboration. Harmonising standards through soft law approaches, as in the case of space debris management, could serve as a model for international cooperation, preventing monopolisation or militarisation of space data.

India must strengthen its position in the global space arena by learning from and collaborating with like-minded nations while fostering innovation within its domestic ecosystem. The path forward lies in driving technological advancements while creating robust frameworks to manage the associated risks.

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