

Future Machines on the Moon: Robotic Autonomy, Human Supervision and the Emerging Security Dimension of Lunar Operations

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Abstract: Lunar exploration has shifted from single flights to a planned buildup of permanent infrastructure. NASA flew four astronauts around the Moon on Artemis II in April 2026, and within eight weeks announced the first three robotic Moon Base missions along with close to a billion dollars in contracts for surface rovers, cargo landers and hopping drones. A parallel programme led by China and Russia, the International Lunar Research Station, is working towards a basic configuration by 2035 with a nuclear power unit delivered between 2033 and 2035. This paper examines the machines that will carry out most of the work in both programmes. It sets out the supervised autonomy model that governs how humans and robots divide decisions under communication delay, identifies the specific artificial intelligence techniques that lunar robots depend on, and proposes an interaction protocol for surface operations. The paper then turns to security. Nearly every capability needed for lunar construction, survey and resource extraction has an obvious military application, and the argument advanced here is that any confrontation on the Moon would be short, machine-led and fought over access to a small number of usable sites rather than over territory in the terrestrial sense. Gaps in the Outer Space Treaty and in the Artemis Accords are assessed against that prospect.

Keywords: Moon, lunar robotics, supervised autonomy, Artemis, Moon Base, International Lunar Research Station, space security, in-situ resource utilisation, Outer Space Treaty

1. Introduction

The Moon is the only natural satellite of Earth, and at a mean distance of about 384,399 km it is close enough that a spacecraft can reach it in a few days and a radio signal in a little over a second. That distance varies through the year from roughly 357,000 to 407,000 km because the orbit is eccentric. The Moon completes a synodic orbit every 29.5 days, and tidal forces have locked its rotation to that period, so the same face has been turned towards Earth for most of the history of the pair. [1][2][3]



Figure 1: The Moon seen from Earth. Its proximity, and the near-continuous sunlight available at a few points near its south pole, are what make sustained operations there plausible.

As a body, the Moon sits awkwardly between categories. Its diameter of 3,474 km is about a quarter of Earth's and its mass roughly 1.2 per cent, which makes it the fifth largest moon in the Solar System and by far the largest relative to its parent planet.[4] Some planetary scientists have argued on geophysical grounds that it should be treated as a planetary-mass object rather than simply as a satellite. Surface gravity is about one sixth of Earth's. There is almost no atmosphere,

no meaningful magnetic field and no hydrosphere. The surface is covered in regolith, a layer of fine, sharp-edged dust and fragmented rock produced by billions of years of impacts. Internally the Moon has the same three-part structure as Earth: a crust of light silicate rock, a mantle, and a small dense core formed as metals sank while the body was still molten. Volcanic activity continued until roughly 1.2 billion years ago, and lava flooding thin-crust basins on the near side produced the dark basalt plains known as maria. The prevailing account of its origin is that debris thrown off Earth by a collision with a Mars-sized body around 4.51 billion years ago coalesced into the Moon shortly after Earth itself formed.[5]

As the Moon consolidated, the lighter materials- rocks with lower densities- rose to the surface while the heaviest materials- metals like iron- sank into the Moon's core. The result is a structure with a thin outer crust, a solid core, and a mostly solid or partially liquid mantle that resembles a chocolate-dipped cherry. [6] [7] These are not neutral facts for anyone planning to operate there. Low gravity changes how a vehicle brakes, turns and digs. The absence of atmosphere rules out aerodynamic flight, parachutes and convective cooling, and means that surface temperatures swing violently between sunlight and shadow. Regolith dust is abrasive, electrostatically charged and gets into seals, bearings, optics and spacesuit fabric. Every machine described in this paper has to be designed against that list.

Interest in the Moon has passed through several phases: observing it, visiting it, and now preparing to stay. The current phase introduces a problem the earlier ones did not have. Once permanent stations exist, and once those stations depend on a small number of sites that combine near-

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continuous sunlight with nearby water ice, the question of who has access to which site stops being academic. A dispute over such a site would not resemble a terrestrial war. There will be no large formations on the Moon, no long supply lines to sustain a campaign, and very few people whose lives anyone would be willing to risk. What could plausibly occur is a short contest over control of equipment and access, conducted almost entirely by machines. That is why the machines themselves, rather than the crews, are the subject of this study. In future, men might participate less actively due to risk of survivability. Development of technologies like robots, drones, and excavators assist or guided by artificial intelligence may play a bigger role. As a result, the functions of these machines are carefully investigated. [8]

1.1 Research Questions

The paper is organised around six questions:

- 1) What technological and operational lessons from Artemis II carry forward into the design of lunar surface robotics?
- 2) What roles will artificial intelligence and autonomous robotic systems take in sustained lunar operations?
- 3) How should authority be divided between human operators and autonomous machines when communication is delayed or interrupted?
- 4) Which capabilities developed for lunar exploration have direct strategic application?
- 5) How would autonomous platforms and AI-based decision-making change the character of a confrontation in space?
- 6) What legal and ethical gaps does this expose?

The method is qualitative. It combines documentary analysis of mission records, contract announcements and agency roadmaps published up to September 2026 with a review of the technical literature on multi-robot autonomy, and it uses scenario construction to reason about outcomes that have not yet occurred. No claim is made here about intentions. The argument is about capability and about what capability tends to invite.

2. Background

2.1 Six decades of lunar missions

Since Russia launched the first trip to moon by Luna 1 in January 1959, there have been 145 missions. Most of them have landed successfully. The Soviet Union, China, India, Japan, Israel, Russia, the United States, Canada, Luxembourg, South Korea, Italy, the United Arab Emirates, Pakistan, and Mexico have all completed their missions to moon. The Soviet Union opened lunar exploration with Luna 1 in January 1959.[9][10] There have been 28 successful soft landings on the moon by five countries. These are China, India, Japan, the Soviet Union, and the United States. The United States successfully landed people on the moon during each of its six Apollo missions. [11][12]. Soft landing is the hard part. Only five national programmes have achieved it: the Soviet2 Union, the United States, China, India and Japan. The United States remains the only country to have landed people, across six Apollo missions between 1969 and 1972.[11][12]

Recent activity has clustered around two things: the far side and the south pole. Chang'e 4 and Chang'e 6 are China's two successful soft landings on the moon's far side. With Chandrayaan-3, India became the first nation to successfully arrive close to the lunar south-polar zone in 2023. Through commercial lunar landers, such as Intuitive Machines' IM-1 (Odysseus) and IM-2 (Athena) missions, the United States has also successfully made landings in the south-polar area. China landed Chang'e 4 on the far side in January 2019 and returned far-side samples with Chang'e 6 in 2024, both supported by relay satellites because there is no direct line of sight to Earth from that hemisphere. India's Chandrayaan-3 touched down in the southern highlands in August 2023, making India the fourth country to soft-land and the first to do so near the south pole. Russia's Luna-25 had attempted the same region days earlier and crashed. Japan's SLIM followed in January 2024. The United States has since returned to the surface through commercial landers rather than government-built ones, with Intuitive Machines placing Odysseus and Athena in the south-polar region on the IM-1 and IM-2 missions. [14][15][16]

Two patterns run through that record. The interesting ground is polar ground, because that is where water ice is thought to survive in permanently shadowed craters. And the entities doing the landing are increasingly private companies operating under government contract.

2.2 Rehearsing on Earth: the ARCHES analogue mission

Before robot teams fly, they are tested on terrain that resembles the target. The clearest example is ARCHES, short for Autonomous Robotic Networks to Help Modern Societies, a project led by the German Aerospace Center. Between 13 June and 9 July 2022, the team ran a demonstration campaign on the slopes of Mount Etna in Sicily, where granular volcanic soil and solidified lava make a reasonable stand-in for lunar ground. [17][18]

The first scenario, Geological Mission I, assumed scientists supervising from Earth. The RODIN lander carried instrument containers. LRU1, a lightweight rover of under 30 kg with navigation, stereo and colour cameras, acted as the scientist of the group, driving to selected rocks, imaging them and returning results to the control centre. LRU2 carried a gripper arm with shovel and gripper hand, moved storage containers, and served as a WiFi repeater so that LRU1 never lost its link. A drone called ARDEA scouted and mapped from above, although high winds limited its use. A second scenario assumed control from an orbital station instead of Earth, and a third deployed low-frequency radio receivers in a fixed geometry as a rehearsal for a far-side array. [19]

What ARCHES demonstrated is not any single piece of hardware. It is the division of labour. A flying scout maps, a science rover observes, an assistant rover manipulates, a lander supplies, and a human team sets goals rather than issuing continuous commands. Every lunar surface architecture proposed since has some version of that arrangement. After numerous other projects the US Artemis project missions from NASA to Moon are the latest which have given good insight into the moon. These have been

lunched in phases as Artemis I to Artemis V. With Artemis I, NASA successfully completed an uncrewed test flight of the SLS (Space Launch System) rocket and Orion spacecraft in Nov. 2022. This mission marked the first launch of the rocket using new exploration ground systems and evaluated Orion's systems without astronauts for the critical life support systems planned for future crewed missions.[20]

3. Artemis II and What It Established

Artemis II was launched in April 2026, on a nearly 10-day voyage around the Moon, marking the first crewed flight of NASA's Orion spacecraft. 20 astronauts Reid Wiseman, Victor Glover, and Christina Koch, along with CSA (Canadian Space Agency) astronaut Jeremy Hansen,

travelled 252,756 miles from Earth, setting a record for the greatest distance humans have travelled in space and observing the lunar surface like never before. Artemis II lifted off from Launch Complex 39B at Kennedy Space Center at 6:35 p.m. EDT on 1 April 2026 and splashed down on 10 April. The crew were Reid Wiseman as commander, Victor Glover as pilot, and Christina Koch and the Canadian Space Agency's Jeremy Hansen as mission specialists. Mission duration was 9 days, 1 hour and 32 minutes, and the Orion spacecraft, named Integrity by its crew, travelled about 700,237 miles in total. It was the first crewed flight beyond low Earth orbit since Apollo 17 in 1972, the first crewed flight of the Space Launch System, and the first flight of Orion with people aboard.[19]

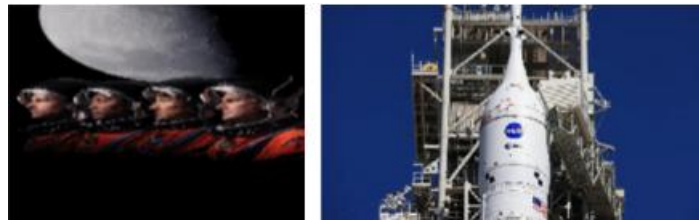


Figure 2: Artemis II. The mission flew four astronauts around the Moon between 1 and 10 April 2026, the first crewed flight beyond low Earth orbit since 1972.

The mission was a test flight and was treated as one. Its objectives were to sustain a crew in the deep space environment through return, exercise ground, flight and recovery systems end to end, retrieve hardware and data for assessment, and validate emergency procedures including abort and rescue as far as was practical. The crew also took manual control for a proximity operations demonstration, flying Orion relative to the spent upper stage on the European Service Module's engines. [19]

Post-flight assessment was broadly positive. NASA reported that SLS met its objectives and that reinforcement applied to the mobile launcher and pad after Artemis I kept damage minimal. One anomaly, a problem with a urine vent line, is under investigation with corrective action planned before Artemis III. On the strength of that data NASA is preparing Artemis III for 2027 as a rendezvous and docking demonstration with commercial landers, with surface missions beginning with Artemis IV in 2028. [19]



Figure 3: Earth seen beyond the lunar limb during Artemis II. Photo: NASA

For the argument of this paper, what matters about Artemis II is not the flight itself but what it confirmed about the shape of the programme behind it. Sending four people around the Moon consumed an enormous rocket, a decade of development and a narrow launch window, and it produced no surface activity at all. Everything that will actually be built on the Moon before 2028 will be built by machines. The crewed programme sets the schedule; the robotic programme does the work.

4. Human Control and Robotic Autonomy

4.1 Supervised autonomy as the operating model

The arrangement now standard for planetary robotics is best described as supervised autonomy. A control centre on Earth monitors the robots, receives engineering and science data, sets objectives and can intervene, but it does not drive. Continuous teleoperation is impractical even at lunar distance, where round-trip light time is about 2.6 seconds, and it becomes impossible during the communication gaps that occur when a relay satellite is out of view or a vehicle enters a shadowed crater. [20]



Figure 4: Supervised autonomy in concept: a servicing robot working on a rover, and a small surface installation being tended by a mixed crew and robot team. Artist concepts

So, the robots decide locally. A rover selects how to route around an obstacle, judges which outcrops are worth approaching, and revises its plan when a neighbouring robot reports something new. A drone surveys ahead and hands updated terrain maps to the ground vehicles. Humans retain what should not be delegated: the mission objective, the safety envelope, and any action whose consequences cannot be reversed.[20]

This is a sensible division, and it is also the point at which the security question first appears. A system built to pursue an objective without waiting for permission is, structurally, a system capable of acting faster than any human can veto. The difference between a survey rover and an armed one is a

payload and a rule set, not an architecture.

4.2 The autonomy stack

Autonomous exploration robots do not run on a single algorithm. They run a layered set of specialised components that exchange information continuously, roughly in the sequence sensors, perception, localisation and mapping, prediction, planning, control, action, and then new observations feeding back into the loop. The higher layers decide what the robot should accomplish; the lower layers decide how to do it without breaking anything. Table 1 summarises the main functions and the techniques associated with each.

Table 1: Functional layers of an autonomous lunar exploration robot. [20]

Function	Techniques commonly used	What it produces
Localisation and navigation	SLAM, sensor fusion across cameras, LiDAR and inertial units, graph and sampling-based path planning, model predictive control	An estimate of where the robot is, a map of what surrounds it, and a drivable route
Terrain mapping and hazard detection	Stereo and depth sensing, semantic segmentation, point-cloud processing, occupancy grids	A 2D or 3D map with traversability probabilities, flagging boulders, slopes, cliffs and loose soil
Science target selection	Image classification, neural feature recognition, anomaly detection, active learning	A ranked list of features worth approaching, with an estimate of expected information gain
Sample handling	Inverse kinematics, sampling-based motion planning, visual surveying, force and torque feedback	A collision-free arm trajectory and a controlled contact with the target
Action selection	Behaviour trees, finite-state machines, probabilistic planning, reinforcement learning within safety constraints	A decision about what to do next given resources and time
Uncertainty handling	Kalman, extended and unscented Kalman filters, particle filters, Bayesian inference	Probability distributions over uncertain states rather than single point estimates
Multi-robot coordination	Distributed planning, task allocation, mesh networking, multi-agent reinforcement learning	Division of an area or task set among several vehicles without central control

Two points about this table deserve emphasis. First, none of these techniques is speculative. All of them have flown or have been field-tested. Second, learned behaviour in real missions is heavily constrained. Reinforcement learning is attractive because an agent can acquire policies about when to explore, when to investigate and when to withdraw, but flight software is validated exhaustively before launch and bounded by hard safety rules at runtime. The autonomy is real; it is not open-ended.[20]



Figure 5: Concepts for surface work: a mixed team handling instrument boxes alongside an excavator, and a heavy walking platform built for rough polar terrain

4.3 CADRE: cooperative autonomy taken to flight

The clearest current demonstration of multi-robot lunar autonomy is CADRE, the Cooperative Autonomous Distributed Robotic Exploration project managed by the Jet Propulsion Laboratory for NASA's Game Changing Development programme. CADRE flies four agents: three solar-powered rovers, each about the size of a carry-on suitcase, and a static base station mounted on the lander. The rovers communicate with each other and with the base station over mesh network radios, and the base station acts as the gateway to Earth while also handling computation on behalf of the team.

The objective is narrow and well chosen. CADRE is meant to show that a team of agents can take a high-level instruction from the ground, something on the order of explore this region, and elaborate it themselves into commands for their own mobility systems and instruments. The rovers cooperatively survey a prescribed area and build a three-dimensional reconstruction of the surface with no human input, then drive in formation taking coordinated

multi-static ground-penetrating radar soundings to map what lies below. Simultaneous measurements from separated positions produce data no single robot could gather. At the centre of the software is a distributed planning, scheduling and execution system that runs on the rovers rather than on Earth.

CADRE is travelling to the Moon on Intuitive Machines' third lunar delivery under the Commercial Lunar Payload Services initiative, bound for the Reiner Gamma region. If it works, it establishes that cooperative autonomy is at flight readiness rather than at laboratory readiness, which is the precondition for everything described in the rest of this paper.

4.4 A proposed human-robot interaction protocol

The following protocol is offered as a practical formalisation of supervised autonomy for surface operations. It is hierarchical and human-in-the-loop by exception rather than by default.

- 1) Objective definition. Before each operational period the mission team states what is to be achieved rather than prescribing movements. Objectives are paired with explicit constraints: keep-out zones, slope and power limits, minimum reserve margins, and a list of actions that require authorisation.
- 2) Plan generation. The robot team produces its own plan against those objectives and constraints and reports the plan, not the route.
- 3) Autonomous execution. The team executes, replanning locally as terrain and sensor data require.
- 4) Continuous self-monitoring. Each agent tracks its own state of health, power budget, thermal margin and localisation confidence against declared thresholds.
- 5) Reporting by exception. Routine progress is

summarised. Anomalies, threshold breaches and genuinely novel observations are escalated immediately.

- 6) Human review. Operators review only the exceptions, and hold sole authority over irreversible or high-risk actions such as drilling, entering a permanently shadowed region, or expending a consumable.
- 7) Objective revision. Findings feed into the next set of objectives, and the cycle repeats.

The value of writing it down in this form is that it makes the boundary of machine authority explicit and auditable. A protocol that says humans supervise says almost nothing. A protocol that enumerates which categories of action require authorisation, and requires that the list be declared before the operational period rather than argued about afterwards, is something an accident investigation can actually examine. That distinction becomes important.

5. The Moon Base Programme: Robotic Infrastructure First

5.1 Why the south pole

NASA announced the Moon Base initiative at its Ignition event on 24 March 2026 and gave the first concrete schedule and contract detail at a briefing at agency headquarters in Washington on 26 May. The programme is structured in three phases across roughly a decade: an initial phase running to about 2029 focused on securing reliable access to the surface and on technology demonstration, a second phase from around 2029 to 2032 establishing initial Moon Base operating capability, and a third phase from 2032 onwards aimed at semi-permanent crewed presence.[21][22][23][24][25]



Figure 6: The three phases of NASA's Moon Base plan, from securing surface access through to semi-permanent crewed presence beyond 2032. Infographic: NASA

The siting decision drives almost everything else. Unlike the equatorial landing sites of Apollo, the south polar region contains elevated ridges that receive near-continuous sunlight while adjacent crater floors have not seen the Sun for billions of years. Those two conditions sit within a few kilometres of each other. The illuminated ridges solve the power problem for part of the year; the shadowed craters are where water ice is believed to have survived, and water ice can be turned into drinking water, breathable oxygen and

rocket propellant. The combination is what makes the region worth the difficulty. [21][22][23][24][25].

The difficulty is considerable. Temperatures inside permanently shadowed regions are among the lowest measured anywhere in the Solar System, thermal swings across the terminator are severe with no atmosphere to moderate them, radiation exposure is unshielded, and the low Sun angle throws long shadows that confuse cameras and

hide obstacles. NASA's position is that the only realistic route into such an environment is to accumulate robotic infrastructure first. As administrator Jared Isaacman put it at the May briefing, the agency does not intend to jump straight to a glass-domed moon base but to work iteratively, generating demand for landers, rovers and technology demonstrations.[21]

5.2 The first three missions

Moon Base I is targeted for launch no earlier than autumn 2026 aboard Blue Origin's Blue Moon Mark 1 cargo lander Endurance, landing on the Shackleton Connecting Ridge. Its payloads look modest on paper and are not. The Stereo Cameras for Lunar Plume-Surface Studies instrument will record how descent thrusters interact with the surface, a question that determines how close two landers can safely be placed and how much abrasive material a landing throws at nearby hardware. A Laser Retroreflective Array will let orbiting spacecraft fix the lander's position precisely. The stated purpose is to reduce risk for the crewed landings from 2028. [21][22][23][24][25]



Figure 7: Moon Base I. Blue Origin's Blue Moon Mark 1 lander Endurance will target the Shackleton Connecting Ridge. Photo: NASA

Moon Base II will fly on Astrobotic's Griffin lander, an infrastructure-class vehicle now handled through Voyager Technologies' Pittsburgh facility, carrying more than 1,100 pounds of cargo. The central payload is Astro-lab's FLIP rover, the FLEX Lunar Innovation Platform, with five NASA instruments mounted on it, and the mission exists to mature surface mobility ahead of the full-size Lunar Terrain Vehicles. Griffin-1 completed mass properties testing in mid-2026 and is scheduled for launch late in the year. [21][22][23][24][25]



Figure 8: Moon Base II, carrying Astro-lab's FLIP rover on Astrobotic's Griffin lander. Photo: NASA

Moon Base III is the science-weighted mission of the three, flying Intuitive Machines' Nova-C lander Trinity on the IM-3 flight with an Altus-1 data-relay satellite alongside. Its anchor investigation is Lunar Vertex, which will study lunar swirls, the bright sinuous markings associated with strong

local magnetic anomalies. The target, Reiner Gamma, coincides with one of the strongest such anomalies known. Payloads from the European Space Agency and the Korea Astronomy and Space Science Institute fly on the same mission. NASA has said these three are the first of more than a dozen Moon Base missions.



Figure 9: Moon Base III, delivering the Lunar Vertex investigation to the Reiner Gamma swirl on Intuitive Machines' Nova-C lander Trinity. Photo: NASA.

5.3 Mobility, power and communications

NASA is not building most of this itself. It is acting as an anchor customer, purchasing delivery and services while commercial providers own and operate the spacecraft. Most early Moon Base flights run through the Commercial Lunar Payload Services programme. Blue Origin, Astrobotic, Intuitive Machines, Firefly Aerospace, Astro-lab and Lunar Outpost are now structural components of the American lunar architecture rather than suppliers to it. [21][22][23][24][25]



Figure 10: The commercial partners now embedded in NASA's lunar architecture through the CLPS programme. Image: NASA.

The contract awards announced on 26 May 2026 totalled roughly \$749 million. Astro-lab received \$219 million and Lunar Outpost \$220 million to build and deliver the first phase of Lunar Terrain Vehicles under firm-fixed-price, milestone-based task orders, with deployment targeted by 2028. Astro-lab's CLV-1 derives from the company's FLEX architecture and is teamed with Axiom Space, Interlune and Odyssey Space Research. Lunar Outpost's Pegasus, partnered with General Motors, Goodyear and Leidos, is designed to operate in manual, autonomous and teleoperated modes for missions lasting up to a year. Blue Origin was awarded \$188 million to deliver both vehicles to the south polar region, with an option period valued at \$280.4 million. Firefly Aerospace received a \$75 million subcontract from the Jet Propulsion Laboratory for Moon-Fall, in which the company's Elytra Dark spacecraft will carry up to four hopper drones on a roughly 45-day transit and release them about 50 km above the surface. The drones descend independently, hop across terrain no rover can reach, and operate for about one lunar

day roughly a mile apart. Launch is targeted for 2028. They draw on Ingenuity Mars helicopter heritage, but in a vacuum, rotors are useless and they must hop on thrusters, which is a different engineering problem. [21][22][23][24][25][26]



Figure 11: The Pegasus rover, designed to work in manual, autonomous and teleoperated modes for missions of up to a year. Photo: Lunar Outpost.

Power and communications are the next constraints. Solar works on the illuminated ridges and fails inside the craters and through the lunar night, so radioisotope heating units are planned to keep vehicles and instruments alive through the cold, with surface fission power under study for later phases.

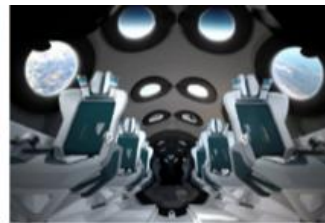


Figure 12: Virgin Galactic's Delta-class programme: assembly of the first vehicle and the cabin fitted for its suborbital profile. Images: Virgin Galactic.

The financial picture behind that delay is instructive. Virgin Galactic reported a net loss of about \$55.9 million for the quarter, an improvement on the \$67.3 million loss a year earlier, with operating expenses down to \$65.1 million. It raised \$134 million through an at-the-market equity programme and ended the quarter with \$286 million in cash and marketable securities while reducing note principal due in 2027 and 2028. Demand was not the problem: the

\$750,000 ticket tranche sold out ahead of schedule, adding more than \$50 million to expected future revenue, and the company retired that price point with plans to open a higher one. The carrier aircraft Eve is expected to ferry the first Delta ship from Mesa to Spaceport America, after which a captive-carry flight and a glide-test campaign precede powered testing.[27]



Figure 13: The Delta-class spacecraft replaces the Unity-class vehicles and is designed for a much higher flight cadence. Images: Virgin Galactic.

Suborbital tourism does not matter to lunar operations in itself. What matters is that the same class of company, under the same capital pressures, is now responsible for delivering cargo landers and rovers to the lunar south pole on dates that a national programme has built its crewed schedule around. Schedule risk in the commercial sector transfers directly into the strategic timeline.

7. The International Lunar Research Station

Roscosmos and the China National Space Administration signed a memorandum of cooperation in March 2021 to build the International Lunar Research Station, a lunar base led jointly by the two agencies and described at the time as open to interested countries and international partners. The published roadmap runs in three stages: reconnaissance through about 2025, construction from 2026 to 2035, and utilisation from 2036, at which point crews would live and

work at the station and use it as a staging point for missions beyond the Moon. The design as presented includes an orbiter, a multi-level surface habitat and a set of rovers, with the south pole as the core location. China's Chang'e-8 mission, planned for 2028, is intended to test the systems needed to build it. [28]



Figure 14: The construction phase of the International Lunar Research Station as presented by Roscosmos.

The membership has widened considerably since 2021. Alongside China and Russia, the programme now lists partners including Azerbaijan, Belarus, Egypt, Kazakhstan, Nicaragua, Pakistan, Senegal, Serbia, South Africa, Thailand and Venezuela, and Chinese officials have described a 555 Project aiming to bring in 50 countries, 500 research institutions and 5,000 overseas researchers. Resource work is explicit in the programme's objectives. Roscosmos researchers presenting in Shanghai described plans to prospect for mineral and water resources, including the possibility of using lunar material as fuel. [28]

Power is where the two programmes diverge most sharply. Roscosmos announced in 2024 that it intended to install a nuclear power unit on the lunar surface with CNSA, and in April 2025 Chinese officials for the first time included a reactor in a formal ILRS roadmap presentation to partner nations in Shanghai. A bilateral agreement followed in May 2025. The target is an automated unit delivered between 2033 and 2035, sized in the tens of kilowatts, installed without human presence. Roscosmos has also discussed nuclear-powered cargo vehicles to carry construction material, although the safety engineering for those is unresolved. The rationale is straightforward: solar arrays cannot carry a base through a 14-day night or supply a crater floor, and battery storage at that scale is impractical. [28]

Two independent programmes are therefore converging on the same few square kilometres of the lunar south pole, on overlapping timelines, with the same interest in the same water ice, and with no shared operating authority between them. Neither China nor Russia has signed the Artemis Accords, and both have criticised them as United States-centric. In the next decade, an international coalition plans to build a lunar research station to transform humanity's exploration and observation of the Moon.

The planning phase is already underway, and it is going well. Construction is slated for 2026 through 2035, and crews could start operating from the base by 2036. The station will feature a lunar orbiter, a large, multi-level, habitat to enable surface-based activities, and play host to several lunar rovers. The station, called the International Lunar Research Station, is a rival to the U.S. space agency's plans to put humans permanently on the surface of the Moon within a similar time

frame. Instead, the ILRS is the brainchild of China and Russia- two of the U.S.' greatest rivals on Earth. [29]

In 2021, Russia and China laid out their roadmap for the station, detailing a timeline that features three main stages:

- 2021-2026: Reconnaissance, featuring three manned missions to the Moon by Russia and China.
- 2026-2035: Build, which will involve creating the autonomously operating station.
- 2036 onwards: Occupancies, meaning crews can live and work at the station and use it as a stop on the way to other space-based mission destinations.

China and Russia plan to build five structures on the Moon's surface. The first will be built for resource extraction to help power the rest of the station. The two countries also issued an invitation for international partners like Saudi Arabia, Thailand, and the European Space Agency to pitch into the effort. [28][29]

While the cooperative memorandum signed by Russia and China in March of 2021 stated the station will be for "multidisciplinary research and multipurpose work," one clear purpose is to study and exploit the Moon's resources particularly, water. [28][29]

In addition to being equipped to study the Moon's geology, ILRS will be able to observe the Moon in great detail, collecting observations of our natural satellite's topography, internal structure, geomorphology, and chemistry. Russia plans to put a nuclear power plant on the moon in the next decade to supply its lunar space programme and a joint Russian-Chinese research station, as major powers rush to explore the earth's only natural satellite.

Russia's space agency, Roscosmos, has unveiled ambitious plans to collaborate with China in constructing an automated nuclear reactor on the moon by 2035. This nuclear reactor aims to provide power to the proposed International Lunar Research Station (ILRS), a joint initiative between Roscosmos and the China National Space Administration (CNSA). The ILRS, conceived in 2021, was initially envisioned as an open lunar base for international collaboration. [30]

The decision to build a nuclear reactor on the moon reflects the challenges of sustaining lunar bases with sufficient power, considering the limitations of solar panels. Roscosmos Director General Yury Borisov announced plans to autonomously install a power unit on the lunar surface around 2033-2035 in collaboration with CNSA. The construction process is expected to be executed without human presence, leveraging nearly ready technological solutions.

Roscosmos envisions employing large nuclear-powered rockets to transport cargo for building the lunar base. However, the agency faces hurdles in ensuring the safe construction of this spacecraft. Meanwhile, the compact nuclear reactor developed by U.K. scientists, powered by small fuel cells, is being tested by NASA for potential use in future missions. [29]

While the specific design of the Russian-Chinese joint reactor remains unclear, it highlights the importance of reliable power sources for sustaining lunar bases. Both Roscosmos and CNSA, with differing lunar exploration track records, are striving to advance space capabilities. Russia faced a setback with the Luna-25 lander crashing on the moon's surface in 2021, while China achieved successful lunar missions, including Chang'e 3, Chang'e 4, and Chang'e 5, with plans for additional lunar endeavours. [29]

Despite collaborative efforts on the ILRS, NASA astronauts may be excluded from visiting due to strained relations with CNSA and Roscosmos. The latter is set to withdraw from the International Space Station by 2025, responding to U.S. sanctions related to Russia's invasion of Ukraine in 2022. While CNSA plans giant reusable rockets for moon missions by 2030, NASA remains committed to returning humans to the lunar surface, albeit with a delayed timeline for the Artemis mission to 2026.[31][32]

8. Future Machines and the Security Dimension

8.1 What the machines will be

Three families of machine will dominate the lunar surface. Drones, in the lunar case propulsive hoppers rather than rotorcraft, will scout terrain that rovers cannot enter, image permanently shadowed regions and stake out sites. [33]

Rovers will range far wider than Apollo crews ever did, carrying crew, cargo and instruments, and operating in manual, teleoperated or fully autonomous modes for periods measured in months. Excavators and construction machines will move regolith for berms, landing pads, radiation shielding and access to subsurface ice. [34] Habitats and power plants will be assembled by these machines before any crew arrives, which is the explicit plan for both the ILRS reactor and NASA's phased buildup.

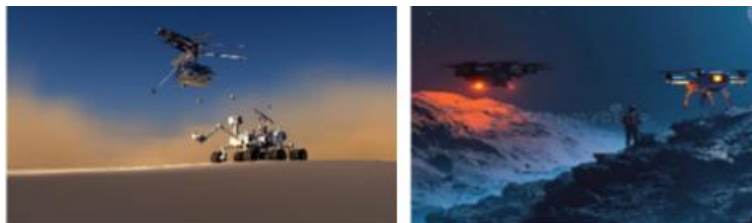


Figure 15: Aerial scouts working with a ground rover, and multi-rotor concepts operating over shadowed terrain. On the Moon such vehicles must hop on thrusters rather than fly.



Figure 16: Surface manipulation and excavation: a robotic arm sampling a boulder during field testing, and a concept for a large regolith excavator supported by a drone team.

Each of these has a military analogue requiring no modification to the platform. A hopper that surveys a crater is a reconnaissance asset. A rover that can navigate autonomously to a coordinate and manipulate hardware with an arm can reach and disable someone else's hardware. An excavator that moves regolith can bury equipment or bulldoze it [34]. A mesh network that lets robots coordinate without ground control is a command network that keeps working when the link to Earth is cut. The dual-use character here is not a matter of interpretation; it is the same capability read against a different objective.



Figure 17: Concept for an early lunar outpost assembled by machines ahead of crew arrival.

8.2 What terrestrial autonomous systems suggest

The terrestrial record gives some indication of direction. Unmanned aerial vehicles have moved in two decades from reconnaissance adjuncts to central instruments of operational planning, and the 2020 conflict between Armenia and Azerbaijan is commonly cited as the point at which drone-enabled reconnaissance and precision strike

visibly altered an outcome, disrupting conventional defensive arrangements while keeping the operating personnel far from the point of effect. Development programmes in the United States, China and Russia have

since pursued strike vehicles with speeds around 1,000 km/h, ranges beyond 2,000 km and payloads measured in tonnes, alongside autonomous decoys and electronic warfare packages.[35]



Figure 18: Terrestrial precedents for autonomous military systems: a quadruped ground robot and a coordinated drone swarm with its command vehicle.

The relevant trend here is the decision loop rather than the hardware. Machine learning and pattern recognition are being applied to compress the interval between observation and action, shortening the management cycle of forces and altering the relationship between operator and outcome. Suchman's work on algorithmic warfare examines how automated target recognition reconstructs what counts as accuracy. Hoijtink's account of prototype warfare describes how Western militaries accelerate emerging technology into operational use through continuous experimentation rather than discrete procurement. [36]

Rauta has argued that much of the vocabulary used for distance-mediated conflict lacks the definitional precision to support analysis, [37] while Horowitz reaches a more cautious conclusion about how much emerging military technology actually shifts international politics. [38] Read together, these accounts suggest that autonomy changes the tempo and the accountability structure of conflict more reliably than it changes who wins.

8.3 What a lunar confrontation would look like

Applying this to the Moon produces a picture quite unlike terrestrial warfare. There will be no large formations, no occupation in any meaningful sense, and no capacity to sustain operations over months. Every item of equipment is expensive, irreplaceable within the mission window and easy to locate, because a powered installation in a vacuum has an unmistakable thermal and radio signature and nowhere to hide. Personnel numbers are small enough that risking them would be politically prohibitive for any government involved.[39]

What follows from those constraints is a specific and limited form of confrontation. It would be short, because nothing can be sustained. It would be about access rather than territory, because the value is concentrated in a handful of ridges and crater rims and in the equipment placed on them. It would be conducted by machines, because the machines are already there and the people mostly are not. And it would most likely be non-kinetic, because kinetic action in a vacuum creates debris and contamination that damages the attacker's own future operations in the same region. Interference with a mesh network, denial of a relay satellite, obstruction of an access route, or simply arriving first and declaring a safety zone would all achieve more at lower cost than destroying anything. That last option is the most likely of them, and it is a

legal act under the current framework.

9. Legal and Ethical Issues

The governing instrument remains the 1967 Outer Space Treaty. Article II prohibits national appropriation of celestial bodies by claim of sovereignty, use, occupation or any other means. Article IV bars nuclear weapons and other weapons of mass destruction in orbit or on celestial bodies and requires that the Moon be used exclusively for peaceful purposes, prohibiting military bases, fortifications and weapons testing. Article I guarantees free access to all areas. The 1979 Moon Agreement went further, declaring lunar resources the common heritage of mankind, and was ratified by no major spacefaring state, which is why it rarely features in operational planning. [40]

Three gaps matter here. The first is that Article IV bars weapons of mass destruction and military installations but says nothing useful about dual-use robotic systems, and essentially everything described in Sections 5 through 8 is dual-use. The second is that Article II prohibits appropriation without defining what degree of exclusive use amounts to appropriation. A permanently occupied site on the one ridge that offers continuous sunlight, surrounded by a declared safety zone, is not a sovereignty claim in form but functions as exclusion in practice. The third is that nothing in the treaty allocates access when two programmes want the same location, and there is no forum with authority to arbitrate.

The Artemis Accords, launched in October 2020 by eight founding states, attempt to fill part of this gap. They are bilateral and non-binding, and they have grown quickly, reaching 70 signatories with Mauritius in July 2026 and 71 when Türkiye signed on 31 August 2026. They affirm the Outer Space Treaty, the Rescue and Return Agreement, the Liability Convention and the Registration Convention, commit signatories to transparency about national space policies, and state that resource extraction does not in itself constitute national appropriation under Article II. That formulation is a compromise rather than a resolution, and the safety zone provision has drawn the sharpest criticism, since a mechanism intended to prevent harmful interference can also operate as one of enclosure. China and Russia are not signatories. [40]

The ethical questions attach to autonomy rather than to

territory. If a machine operating under supervised autonomy damages another state's asset during a communication gap, responsibility has to be assigned somewhere, and the Liability Convention was not drafted with delegated machine decisions in mind. The protocol proposed in Section 4.4 is one partial answer: declaring in advance which categories of action require human authorisation makes the boundary of machine discretion auditable after the fact. A second is mutual transparency. Both programmes already publish mission plans and both already track each other's landers, so an obligation to register surface positions and planned traverses would cost little and remove a great deal of ambiguity. Neither measure requires anyone to trust anyone.

10. Discussion and Conclusion

The findings can be stated compactly. The centre of gravity in lunar exploration has moved from crewed flight to robotic infrastructure, and the crewed missions now depend on machine-built groundwork rather than the other way round. The operating model for those machines is supervised autonomy, and CADRE indicates that cooperative multi-robot autonomy is at flight readiness rather than concept stage. [41] The programme is carried by commercial contractors whose schedules and balance sheets have become strategic variables. Two large efforts, the American Moon Base programme and the Chinese and Russian ILRS, are converging on the same small region of the south pole across the same decade, drawn by the same combination of near-continuous sunlight and accessible water ice.

From that convergence a security dimension follows without anyone having to intend it. The technologies that make lunar construction possible, namely autonomous mobility, manipulation, excavation, mesh communications and machine target selection, are the same technologies that would make interference possible. The most plausible form of confrontation is brief, robotic, non-kinetic and concerned with access rather than with ground held. The most plausible first move is not an attack but an arrival, since occupying the best site and declaring a safety zone around it achieves exclusion at no political cost and violates nothing in the current legal framework. (42)

The legal framework is the weakest element in this picture. The Outer Space Treaty addresses weapons of mass destruction and formal sovereignty claims, neither of which describes what is actually being built. The Artemis Accords are non-binding, do not include the two states behind the competing programme, and leave the safety zone concept undefined at its edges. Nothing allocates access, and nothing assigns responsibility for the actions of a machine operating outside a communication window.

Three recommendations follow: The boundary of machine authority should be specified in advance and in writing for every surface operation, so that delegated decisions can be examined afterwards. Surface positions, planned traverses and declared safety zones should be registered and published, a measure costing both programmes almost nothing while removing most of the ambiguity that could otherwise be read as hostile. And dual-use robotics needs to be addressed explicitly rather than left to an Article IV

drafted for a world of missiles and garrisons. [51][52]

None of this is remote. Moon Base I is expected to launch within months of this writing, the first Lunar Terrain Vehicles and the Moon-Fall drones are contracted for 2028, Artemis IV is scheduled for the same year, and the ILRS reactor is targeted for delivery between 2033 and 2035. The machines described here are being built now.

The research aims to determine the disruptive technologies and the challenges to existing arms control regimes. The paper has discussed the emergence of fourth industrial revolution and its military implications. However, the major focus of the research is the impact of counter-space capabilities, AI-based cyberwarfare, and hypersonic weapons on the arms control regime. [53]

The increasing complexity of the contemporary security environment, the expansion of operational domains, and the transformation of information superiority into a decisive factor have brought multidomain operations to the forefront as one of the principal forms of modern military activity. Such operations require a high level of synchronization of parallel and interrelated actions across land. [54]

References

- [1] Wieczorek, M.A. et al. (2006) "The constitution and structure of the lunar interior", *Reviews in Mineralogy and Geochemistry*, 60(1), pp. 221-364.
- [2] Williams, D.R. (2006) "Moon Fact Sheet", NASA/National Space Science Data Centre, Greenbelt, MD.
- [3] Lang, K.R. (2011) *The Cambridge Guide to the Solar System*, 2nd edn. Cambridge: Cambridge University Press. ISBN 978-1-139-49417-5.
- [4] Morais, M.H.M.; Morbidelli, A. (2002). "The Population of Near-Earth Asteroids in Co-orbital Motion with the Earth". *Icarus*. 160 (1): 1–9. Bibcode:2002Icar..160. 1M. doi:10.1006/icar.2002.6937. hdl:10316/4391.
- [5] Metzger, P. et al. (2022) "Moons are planets: scientific usefulness versus cultural teleology in the taxonomy of planetary science", *Icarus*, 374, 114768.
- [6] Williams, David R. (February 2, 2006). "Moon Fact Sheet". NASA/National Space Science Data Center. Archived from the original on March 23, 2010. Retrieved December 31, 2008.
- [7] <https://science.nasa.gov/moon/>
- [8] Prabhat Mishra Battle vs War: Check the Difference Between Battle and War, Josh, Mar 31, 2026, 12:08 IST
- [9] Wade, Mark. "Luna E-1". *Encyclopedia Astronautica*. Archived from the original on 22 December 2010. Retrieved 3 December 2013.
- [10] "Chandrayaan-2 landing: 40% lunar missions in last 60 years failed, finds Nasa report". 7 September 2019. Archived from the original on 8 September 2019. Retrieved 28 June 2022.
- [11] "First commercial mission to the Moon launched from China". *Spaceflight Now*. 25 October 2014. Retrieved 24 July 2015.
- [12] "Pioneer 0". US National Space Science Data Centre.

- Archived from the original on 19 December 2021. Retrieved 3 December 2013.
- [13] "Pioneer 1". US National Space Science Data Centre. Archived from the original on 5 April 2022. Retrieved 3 December 2013.
- [14] "China Readies Moon Mission for Launch Next Week". Space.com. 14 October 2014. Retrieved 24 July 2015.
- [15] Siddiqi, Asif A. (2002). "1958" (PDF). Deep Space Chronicle: A Chronology of Deep Space and Planetary Probes 1958–2000. Monographs in Aerospace History, No. 24. NASA History Office. pp. 17–19. Archived (PDF) from the original on 12 February 2013. Retrieved 12 July 2017.
- [16] "Pioneer 1". US National Space Science Data Center. Archived from the original on 5 April 2022. Retrieved 3 December 2013.
- [17] <https://www.nasa.gov/analog-missions/>
- [18] German Aerospace Centre (DLR), "ARCHES space-analogue demonstration mission". Available at: <https://www.dlr.de/en/research-and-transfer/projects-and-missions/arches>
- [19] German Aerospace Center (DLR) (2022) "Robotics team practises lunar exploration on Mount Etna", 1 July 2022.
- [20] Gregg Rabideau, Joseph Russino, Andrew Branch, Nihal Dhamani, Tiago Stegun Vaquero, Jean-Pierre de la Croix, Federico Rossi Multi-Robot cooperative autonomy on the moon: The cadre Technology demonstration Mission, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, Chromeextension://efaidnbmnmbpcajpcglclefindmkaj/ <https://ai.jpl.nasa.gov/public/documents/papers/CADR-E-ASTRA-2025-Extended-Abstract.pdf> (b) Rabideau, G. et al. (2025) "Planning, scheduling, and execution on the Moon: the CADRE technology demonstration mission", arXiv:2502.14803, Jet Propulsion Laboratory, Caltech. (c) de la Croix, J.-P. et al. (2025) "Multi-robot cooperative autonomy on the Moon: the CADRE technology demonstration mission", Proc. 18th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA), Leiden.
- [21] NASA Jet Propulsion Laboratory, "CADRE (Cooperative Autonomous Distributed Robotic Exploration)". Available at: <https://www.jpl.nasa.gov/missions/cadre/>
- [22] <https://www.nasa.gov/mission/artemis-ii/>
- [23] <https://www3.nasa.gov/specials/artemis/index.html>
- [24] <https://www.nasa.gov/mission/artemis-ii/>
- [25] NASA, "Artemis II: NASA's First Crewed Lunar Flyby in
- [26] NASA (2026) "NASA Answers Your Most Pressing Artemis II Questions", April 2026. 25. Guy Faulconbridge, Russia plans a nuclear power plant on the moon within a decade, Reuters, December 25, 2025
- [27] NASA (2026) "NASA on Track for Future Missions with Initial Artemis II Assessments", 20 April 2026.
- [28] NASA (2026) "NASA Provides Update on Moon Base Rovers, Landers, Missions", news release, 26 May 2026. (a) NASA, "Moon Base Phases". Available at: <https://www.nasa.gov/moonbase-phases/>
- [29] Foust, J. (2026) "NASA selects four companies for initial moon base awards", SpaceNews, 26 May 2026. (c) SpacePolicyOnline (2026) "NASA Awards Initial Moon Base Rover and Lander Contracts", 26 May 2026. (d) Spaceflight Now (2026) "NASA outlines nearly \$1 billion investment into initial Moon Base missions", 27 May 2026. (e) NASA, "The Artemis Accords". Available at: <https://www.nasa.gov/artemis-accords/> (f) United States Department of State, "Artemis Accords", Bureau of Oceans and International Environmental and Scientific Affairs.
- [30] (a) Virgin Galactic, Spaceflight Expeditions <https://www.virgingalactic.com/> (b) Space.com (2026) "Virgin Galactic delays next commercial spaceflight to 2027", 13 August 2026.
- [31] (a) Russia, China Sign Memorandum on Cooperation in Creating Lunar Research Station, March 9, 2021, <https://russiabusinessstoday.com/technology/russia-china-sign-memorandum-on-cooperation-in-creating-lunar-research-station/> (b) <https://foreignpress.org/journalism-resources/what-to-know-about-russia-and-chinas-joint-plan-for-a-nuclear-reactor-on-the-moon-by-2035>. (c) Baptista, E. (2025) "China, Russia may build nuclear plant on moon to power lunar station, official says", Reuters, 23 April 2025.
- [32] The construction phase...Roscosmos / Twitter screenshot
- [33] Guy Faulconbridge, Russia plans a nuclear power plant on the moon within a decade, Reuters, December 25, 2025
- [34] <https://foreignpress.org/journalism-resources/what-to-know-about-russia-and-chinas-joint-plan-for-a-nuclear-reactor-on-the-moon-by-2035>
- [35] https://www.researchgate.net/publication/390559630_Future_armed_conflicts_the_role_of_advanced_military_technologies_in_shaping_warfare_strategy
- [36] https://www.researchgate.net/publication/390559630_Future_armed_conflicts_the_role_of_advanced_military_technologies_in_shaping_warfare_strategy
- [37] John P. Rafferty, Regolith Geology, Britannica
- [38] Andre Ripla, Autonomous Terraforming Systems: Reshaping Planetary Environments Through Intelligent Automation, Digital Insights, March 13, 2026.
- [39] Marijn Hoijsink 'Prototype warfare': Innovation, optimisation, and the experimental way of warfare, European Journal of International Security, Cambridge University Press: 17 May 2022
- [40] <https://wiki.warframe.com/w/Rauta>
- [41] <https://www.kipedia.org/wiki/ArtemisII>
- [42] Smithsonian confrontation, https://www.si.edu/object/nasm_A19760332000
- [43] Anne Uruegi Agi, University of Calabar Beyond Earth Orbit: Legal and Policy Challenges of Human Settlements on The Moon and Mars, November 2025. https://www.researchgate.net/publication/410049821_Beyond_Earth_Orbit_Legal_And_Policy_Challenges_Of_Human_Settlements_On_The_Moon_And_Mars
- [44] https://www.researchgate.net/publication/390559630_Future_armed_conflicts_the_role_of_advanced_military_technologies_in_shaping_warfare_strategy

- uture_armed_conflicts_the_role_of_advanced_military
_technologies_in_shaping_warfare_strategy
- [45] United Nations (1967) Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies. UNOOSA.
 - [46] United Nations (1979) Agreement Governing the Activities of States on the Moon and Other Celestial Bodies. UNOOSA.
 - [47] Akhundov, R. (2025) "Future armed conflicts: the role of advanced military technologies in shaping warfare strategy", National Defence University of the Republic of Azerbaijan.
 - [48] Horowitz, M.C. (2020) "Do emerging military technologies matter for international politics?", *Annual Review of Political Science*, 23, pp. 385-400.
 - [49] Hoijtink, M. (2022) "'Prototype warfare': innovation, optimisation, and the experimental way of warfare", *European Journal of International Security*, 7(3), pp. 322-336.
 - [50] Rauta, V. (2021) "A conceptual critique of remote warfare", *Defence Studies*, 21(4), pp. 545-572.
 - [51] Suchman, L. (2020) "Algorithmic warfare and the reinvention of accuracy", *Critical Studies on Security*, 8(2), pp. 175-187.
 - [52] Rosen, S.P. (1988) "New ways of war: understanding military innovation", *International Security*, 13(1), pp. 134-168.
 - [53] Ahsan Saeed, Ghulam Mujaddid, March 2026
 - [54] Siyavush Mammad Babayev, Ramil Akhundov, Elshan G. Hashimov, The Future of Military Technological Development and its Impact on International Stability, March 2023