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INTEGRATION OF COMBINED JOINT ALL DOMAIN COMMAND AND CONTROL FOR THE PURPOSES OF THE PROJECTS UNDER THE SIMULATION EXPLORATION EXPERIENCE PROGRAM

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Abstract: *The article examines the LUNARITE simulation project of the Nikola Vaptsarov Naval Academy in the international simulation program Simulation Exploration Experience. The main objectives and results of the LUNARITE project are discussed. Their implementation methods and how they align with Simulation Exploration Experience and NASA's Artemis programs are also discussed. A detailed review is made of the integration of Combined Joint All Domain Command and Control in the LUNARITE project and its significance for future space mission.*

ИНТЕГРИРАНЕ НА КОМБИНИРАНО СЪВМЕСТНО КОМАНДИРАНЕ И КОНТРОЛ ВЪВ ВСИЧКИ ОБЛАСТИ ЗА ЦЕЛИТЕ НА ПРОЕКТИТЕ ПО ПРОГРАМАТА SIMULATION EXPLORATION EXPERIENCE

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Резюме: *Статията разглежда симулационния проект LUNARITE на Военноморската академия „Никола Вапцаров“ в рамките на международната симулационна програма Simulation Exploration Experience. Обсъждат се основните цели и резултати от проекта LUNARITE. Разгледани са и методите за тяхното изпълнение и как те се вписват в програмите Simulation Exploration Experience и Artemis на НАСА. Направен е подробен преглед на интегрирането на Combined Joint All Domain Command and Control в проекта LUNARITE и неговото значение за бъдещи космически мисии.*

Overview of the Simulation Exploration Experience program

The Simulation Exploration Experience (SEE) represents a pioneering, distributed platform designed to engage university teams worldwide [1] in the collaborative design, development and execution of future space mission simulations. Fundamentally grounded in open, standards-based modeling and simulation, SEE serves a dual mission: educationally, it equips students with workforce-relevant competencies in real-time distributed modeling and simulation (M&S) and technically, it demonstrates the interoperability of heterogeneous simulation components, named federates, that collectively model complex space scenarios, including lunar surface operations, cislunar activities, and planetary missions sometimes even to Mars.

Originating from the “Simulation Smackdown” challenge in 2011, SEE has matured into a robust, standards-centric learning and research environment that explicitly aligns its scenarios with NASA’s Artemis program architecture and backed from Florida Space Institute and Kennedy Space Center. This alignment has transitioned its scope from far-future speculative missions toward tangible mid-century capabilities such as the Artemis Base Camp and Gateway orbital activities. This provides participants with an authentic, systems-thinking framework centered on designing systems, defining behaviors and orchestrating interactions, all essential for understanding multifaceted space mission dynamics.

Programmatically, SEE operates on an annual cycle culminating in an international event where teams across continents demonstrate integrated simulations, receiving critical feedback from academic, industry and government mentors. Its hybrid format combines asynchronous development phases with synchronous technical milestones and live federation executions across global time zones. Lessons from the 2018 cycle, hosted in Sofia, Bulgaria [2], highlight SEE's deeply international nature and its emphasis on mentoring, employability and community building.

The program structure includes a preparatory "Kick-Start" phase typically in September, a formal start in January and tiered engagement levels allowing institutions to select their commitment depth from observers to active participants. The scenario language embodies a systems–behaviors–interactions model, which provides a pedagogical scaffold while accommodating innovation. This framework is intricately tied to Artemis-aligned, south-polar lunar, and cislunar mission narratives, enriching the educational context.

Technically, SEE's backbone is the IEEE High-Level Architecture (HLA, 1516) standard [3], providing the runtime infrastructure, object model template, and integration rules for coordinated, time-managed simulation interactions. Given HLA's complexity, SEE supplements standards adherence with accessible development toolkits, tutorials, and mentoring. Teams develop federates, author FOM-compliant XML, and manage interaction publications through HLA's RTI services. Simulation states are visualized in NASA's Distributed Observer Network (DON) [4], which maps federate states to 3D assets for a common operational picture. Over time, SEE's technological suite has broadened to include NASA's Trick Simulation Environment and JSC Engineering Orbital Dynamics (JEOD), reducing low-level integration effort and empowering students to focus on mission logic rather than infrastructure. The SEE HLA Starter Kit advances these efforts, supporting open-source and commercial toolchains, fostering code reuse, and accelerating competency development in distributed simulation. To address domain-specific challenges, such as coherent celestial reference frames, strict time synchronization, and long-duration mission scenarios, SEE adopts the SISO Space Reference Federation Object Model (SpaceFOM) [5] as its standard baseline. SpaceFOM extends beyond data models to define critical execution roles, comprehensive compliance rules, and essential federation agreements, institutionalizing reusable patterns for execution control, spatial referencing, and time management. This institutionalization enables seamless onboarding of new teams, essential for geographically dispersed academic collaborations bound by fixed timelines. Visualization is further enhanced via DON, which renders federate states using defined metadata and coordinate transforms, ensuring spatial and temporal consistency across federations. Beyond visualization, DON acts as a real-time sanity checker aligning federate publications.

The SEE process emphasizes transparency and coordination through artifacts such as "Baseball Cards" that describe federate capabilities and interfaces and interaction matrices detailing intended data exchanges and temporal couplings. This documentation links tightly with SEE's educational framing and informs SpaceFOM's execution agreements and compliance assessments, clarifying responsibilities and enabling systematic testing. From a standards perspective, SEE functions as a living laboratory for evolving space simulation standards like SpaceFOM and HLA. Teams validate execution patterns, refine modules, and feedback into standards development, fostering a synergistic relationship where standards shape practice and practical deployments inform standards refinement. SEE's sustained implementation of SpaceFOM underscores its role as the benchmark for space-domain distributed simulation.

Finally, SEE's explicit alignment with the Artemis program [6] and Moon-to-Mars initiatives situates it at the forefront of future space operations research. Its insistence on a-priori interoperability, use of a shared visualization environment and rigorous documentation framework create an ideal testbed for exploring mission-partner data exchanges, latency constraints and coalition governance. In this way, SEE transcends pure education to become a strategic innovation platform supporting the development and demonstration of critical capabilities for interoperable, multi-actor lunar and cislunar missions. This comprehensive integration of technical rigor, pedagogical structure, international collaboration and standards stewardship makes SEE a unique and potent instrument for preparing the next generation of space mission engineers and advancing the state of the art in distributed space mission simulation.

Stages in the development of LUNARITE. Goals and objectives

Since 2018, the Nikola Vaptsarov Naval Academy (NVNA) [7] has fielded mixed teams of military cadets and civilian students to participate in the SEE. These teams are deliberately structured into four functional subgroups, like scientific research, concept design, 3D modeling and software engineering, so that each mission concept is simultaneously scientifically grounded, visually and functionally specified and executable in a distributed simulation environment. The research subgroup formulates mission aims, site selection, and operating concepts, concept artists translate these aims into vehicles, habitats,and infrastructure, 3D modelers produce low-overhead, simulation-ready assets (typically in OBJ), and programmers implement federates that interoperate through HLA and the SpaceFOM extensions used by SEE. This scaffolding mirrors real mission design workflows and has proven effective for NVNA's earlier SEE work on lunar bases, cislunar stations, and research rovers, where teams moved from concept to local tests and finally to Internet-scale federation with other universities.

A typical NVNA [8] development cycle begins with a local integration on a lab RTI using the SEE "Lunar Rover" demo to validate the build environment and message flow. After local tests pass, teams bring the NASA Distributed Observer Network visualizer online by joining its federate, which listens to federation traffic, transforms it into XML, and renders the scene in real time or replay. Only after the local/demonstrator gates are cleared does the team request credentials for the remote federation server, provided to SEE teams via Florida Space Institute, connect through VPN, and begin joint rehearsals with partner universities. This stair-step approach starting from demo, local integration, DON visualization and remote federation has become an internal standard of practice at NVNA.

The 2023 LUNARTEC concept established the baseline that LUNARITE would build upon. LUNARTEC envisioned a multi-layered lunar base located near the south pole and tied into the Gateway orbital infrastructure. Its elements included logistics hubs, research laboratories, habitation biospheres, mobility assets, habitat and explorer rovers, a heavy-lift hopper for cross-terrain cargo, ISRU for alloys, aerogels and regolith-derived cements and additive-manufacturing cells for spares and structural components. While the 2023 concept details were advanced within the NVNA team, several enabling patterns it employed are well aligned with SEE standard practice: adopting HLA/SpaceFOM for a-priori interoperability, using DON for common visualization and organizing the project's systems–behaviors–interactions early to ease federation integration. These same patterns are emphasized in the 2024 SEE Event Scenario, which directs teams to structure their work as Systems (student designs), Behaviors (what systems do) and Interactions (how systems communicate).

LUNARITE advances from a capability-centric base to an orchestrated, command-and-control-aware settlement. The central design decision is to adapt the Combined Joint All-Domain Command and Control (CJADC2) paradigm into a lunar context that includes coalition partners and mixed civil–military assets. In practice, five objectives shape the 2024 system:

1. Autonomous reconnaissance drones (sense): deploy a family of small aerial and hopper-type UAVs to map shadowed craters, characterize regolith, and scout routes.
2. AI-assisted rovers with adaptive learning (sense/make sense) [9]: integrate onboard perception and path-planning with ground-based fusion to improve traverse safety and sampling yield.
3. Ground–orbital relay network (transport): maintain resilient communications across line-of-sight disruptions via mast relays, surface repeaters, and Gateway-mediated links.
4. Semi-autonomous operations for real-time and predictive decision-making (make sense/act): prioritize work orders, re-task assets when contingencies arise, and pre-position power or spares based on forecasts.
5. Standards-based integration for coalition partners (governance): use SpaceFOM/HLA roles, documentation, and compliance rules to provide a predictable integration surface for external federates.

These objectives reflect current CJADC2 guidance emphasizing data-centricity, interoperability, and decision advantage. In defense contexts, the U.S. CJADC2 Cross-Functional Team, co-led by Joint Staff J6 and the Chief Digital and AI Office, highlights the need for shared data fabrics and common governance so that distributed sensors and effectors can be synchronized. Translating this to the Moon, LUNARITE treats each rover, habitat or relay as a data-producing/consuming node, and the SpaceFOM Master, Pacing, and Root Reference Frame Publisher roles supply the timing, execution control, and reference-frame scaffolding needed for a cohesive federation. LUNARITE follows a stage-gated plan that maps directly to SEE's academic calendar – Kick-Start in late September, official start second Wednesday in January, integration through spring – and NVNA's internal rehearsal cadence.

In LUNARITE, reconnaissance drones, AI-enabled rovers, fixed sensors and Gateway relays act as a distributed sensor grid. From a CJADC2 perspective, the aim is to minimize the observe to orient time by normalizing disparate data into a common schema at the federation boundary and maintaining assured transport even when line-of-sight is compromised. SpaceFOM's [10] pacing/time-management rules and reference frames ensure that sensor data are temporally and spatially coherent, a prerequisite for reliable fusion. LUNARITE aggregates status, plans and predictions in a mission hub that emulates the data fabric, where common data services, access control (zero-trust principles) and governance allow multiple decision aids to subscribe and act. Practically, this includes rover hazard maps, relay link budgets, and logistics burn-down charts. The goal is decision advantage: presenting the right option to the operator (or to autonomy) before conditions close a window of opportunity. The mission hub issues tasking messages to assets, re-prioritize queues, and redistributes power or spares. In coalition terms, this is where gateway functionality matters: a C2 broker pattern translates formats while preserving authoritative data. Defense C2 gateways such as ADSI illustrate how rapid data-type onboarding and protocol translation sustain interoperability among heterogeneous participants, by analogy, LUNARITE's gateway module is designed to accept partner formats and expose normalized interactions to the federation.

NVNA's participation in SEE previously produced a Mobile Lunar Base simulation emphasizing AI-supported movement, biosphere control, and cybersecurity. Lessons from that work inform LUNARITE's focus on cyber-hardening and mission management: decision aids are only as good as their data integrity and access controls. The programmatic cadence of SEE continues to provide a structured on-ramp for new students and a venue for advanced integration by returning cohorts. Incorporating CJADC2 principles into a lunar mission simulation does more than add autonomy. It forces early articulation of who can see what, when, and why – and how decisions propagate across organizational and technical boundaries. By treating every rover, drone, habitat, and relay as a participant in a governed data ecosystem – and by embedding a priori interoperability via SpaceFOM – LUNARITE aims to demonstrate that decision advantage can be engineered into exploration architectures from the outset. This is consonant with SEE's trajectory from far-future vignettes to Artemis-aligned infrastructure and with the broader shift toward distributed, resilient C2 in contested environments.

Integrating CJADC-2 into space missions

Combined Joint All-Domain Command and Control (CJADC2) [11] is the U.S. Department of Defense's strategic initiative aimed at achieving decisive warfighting advantage by enabling decision-making at the speed of relevance. CJADC2 accomplishes this by seamlessly connecting sensors, platforms, and decision aids across all military services and coalition partners to produce a unified, real-time operational picture across multiple domains, including land, sea, air, space, cyber, and electromagnetic spectrum. Its core operational concept is a streamlined cycle: Sense, Make Sense, and Act, which is implemented through data-centric, interoperable architectures, common governance frameworks, and rapid, iterative fielding of capability increments. CJADC2 evolved from the initial JADC2 strategy by explicitly incorporating multinational coalition realities and the Mission Partner Environment (MPE), highlighting that decision superiority must transcend national boundaries, heterogeneous systems, and security domains. This expansion is critical to ensuring coalition cohesion and trust while shortening time from observation to prioritized action, not merely increasing bandwidth or connections. Practitioners emphasize that CJADC2's success hinges on software-defined mission outcomes: delivering the right data to the right toolsets just as human decision-makers need them, supported but not overwhelmed by automation.

CJADC2's architecture [12] is organized into three integrated Lines of Effort (LOEs): the Data Enterprise, which standardizes access, policies, and schemas for common data sharing. Technical Enterprise, responsible for ensuring transport, cloud services, and cross-domain interoperability. Human Enterprise, focusing on tactics, training, workflows, and trust in human-machine teaming. Together, these LOEs enable end-to-end mission threads that are tested and refined in iterative experiments and exercises, such as those demonstrated by programs like the Advanced Battle Management System (ABMS), Space Development Agency's Battle Management Command and Control (BMC3), Project Convergence, and Project Overmatch. These efforts emphasize rapid capability fielding through DevSecOps practices and foundational architecture principles such as zero trust and cross-domain solutions embedded from inception.

In space operations specifically, CJADC2 manifests in mission threads with well-defined data custody, fusion, and decision timelines. For example, missile warning and tracking relies on heterogeneous space- and ground-based sensors exchanging cues with tactical command centers at machine speed, enabled by CJADC2's common data products, cross-domain authenticated transport, and human training for load management. Space Domain Awareness (SDA) similarly harnesses sensor fusion across government and commercial sources through enforced non-proprietary interfaces and zero-trust gateways to protect sensitive data while allowing partner collaboration. Tactical satellite communications and dynamic satellite tasking require agile reallocation of bandwidth and latency capacities amidst contested environments, supported by continuous Authority To Operate and containerized deployment of waveform translators and payload software, dramatically shortening response times.

Operationally, CJADC2 space command and control can be visualized in a four-tier architecture connected by a governed data fabric: the On-Orbit Edge (satellites with crosslinks and onboard processing), Ground Entry/Relay nodes (gateways and tactical edges), Operations Centers (Combined Space Operations Centers and service Air Operations Centers) and the Joint/Coalition Mission Cloud (accredited cloud environments running fusion analytics and orchestration). Within and between these tiers, C2 gateways normalize and translate legacy and modern data formats, enforce security policies and provide resilient fallback options, enabling integrated, survivable command chains across multinational domains.

Practically, gateways like the modernized Air Force Advanced Data Services Interface (ADSI) [13] exemplify the requirements for multi-link brokering, containerized deployments and rapid reauthorization cycles critical for real-world CJADC2 operations. For space missions, analogous gateways mediate between satellite telemetry, tactical links, commercial ground services and coalition enclaves, significantly reducing operator burden and accelerating command decision cycles.

Multinational space collaboration, covering missile warning, debris attribution and coalition SATCOM, relies heavily on Mission Partner Environment constructs and robust joint doctrine such as CJCSI 6290.01A [14]. This playbook coordinates mission impact assessments, materiel and doctrinal adjustments and ensures partners achieve interoperability from Day 1 without resorting to ad hoc integrations. However, challenges persist as proprietary interfaces and non-standard APIs inhibit system evolution and rapid integration, a concern highlighted by governmental audit agencies. Programs are strongly encouraged to adopt Modular Open Systems Approaches (MOSA) [15] and enforce open interface standards contractually, especially for incorporating commercial space data within national and allied sensor networks supporting time-sensitive warning timelines.

CJADC2's evolutionary nature is underscored through continual technology maturation via live demonstrations and war games. These events foster innovation in human-machine teaming, sensor fusion and resilient networking, including countering autonomous threats and swarm tactics, building a foundation that extends seamlessly between terrestrial and space operational domains [16]. Yet, institutional gaps remain, such as insufficient lessons-learned dissemination, which could slow enterprise-wide adoption and operationalization of CJADC2's promising capabilities.

In summary, CJADC2 is not merely a connectivity or data-sharing program but a transformational concept enabling integrated, coalition-aware, domain-spanning command and control. Through iterative development, open standards, layered architectures, and a joint commitment to human-machine collaboration, CJADC2 aims to shorten decision cycles, improve situational awareness, and maintain strategic information advantage.

Conclusion

SEE and NVNA's LUNARITE together highlight how a standards-driven academic ecosystem can evolve into a credible proving ground for space command-and-control concepts. By adopting the IEEE High-Level Architecture standard together with SpaceFOM from the start, SEE integrates interoperability as a core design principle rather than an afterthought. Its framework of systems, behaviors, and interactions, combined with NASA's Distributed Observer Network for shared visualization and rigorous documentation like baseball cards and interaction matrices, enables globally dispersed teams to build time-synchronized, coherent federations. NVNA's mixed cadet and civilian teams translate scientific objectives into executable simulation assets, progressing methodically from local testing to large-scale international federation exercises.

LUNARITE builds on this foundation by embedding the Combined Joint All-Domain Command and Control (CJADC2) decision cycle Sense, Make Sense and Act, within lunar mission operations. Autonomous drones and AI-enabled rovers generate data fed into a governed data fabric where SpaceFOM's standardized roles maintain temporal and spatial consistency. A gateway broker pattern ensures secure, standardized data exchange and enforces command policies, enabling timely tasking and coordination among surface and orbital assets. This creates not only a functional simulation federation but also an instrumented decision system measuring critical metrics such as decision latency, communication reliability, situational awareness, and interoperability, directly supporting the goal of decision advantage.

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