Enabling Interoperable Digital Twins for Collaborative Lunar Exploration [1]

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Abstract - **We present the results of a proof-of-concept development for standard-based interoperability between distributed and disparate Digital Twins (DT) systems for lunar exploration. The project was undertaken by a team from NASA Jet Propulsion Laboratory (JPL), California State University, Northridge (CSUN), Verses AI Inc., and the Spatial Web Foundation. Leveraging the soon-to-be-approved IEEE P2874 Spatial Web standard, the team developed and demonstrated real-time, cross-platform collaborative lunar explorations between DT systems at JPL and CSUN. Using a spatial web plug-in from Verses AI Inc., the team demonstrated real-time joint testing of a lander model at CSUN and a rover DT model at JPL on distributed NVIDIA Omniverse platforms via standard-based spatial web protocols. Additionally, cross-platform collaborations between Omniverse and Unity platforms were demonstrated using these protocols. The team also showcased intellectual property protection by executing a Physics-Informed Neural Network (PINN) model remotely at JPL while testing the model at CSUN. To our knowledge, this project marks the first demonstration of interoperability between distributed and disparate DT systems using the spatial web standard.**

TABLE OF CONTENTS

1. INTRODUCTION

Digital Twins (DTs) [1] [2] hold immense potential to transform various fields such as science, technology, engineering, production, and operations. They have already been successfully applied in domains such as scientific discovery, biomedical sciences, factory management, climate change modeling, and smart city development. In the context of lunar exploration—where direct access to objects in space is highly challenging—DT technology is particularly vital. DTs enable engineers on Earth to monitor and manage the health of systems operating on the Moon and facilitate the virtual planning and testing of lunar activities before robotic systems perform potentially hazardous tasks. Additionally, DTs can simulate a wide range of lunar missions, aiding stakeholders in determining their roles from both operational and financial perspectives. This capability can guide government agencies in assuming responsibility for mission components that private and commercial entities may be unable to manage. As lunar exploration increasingly becomes a collaborative international endeavor, DTs have the potential to support global cross-organizational testing and coordination. Given these critical advantages, we consider

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DTs an essential requirement for ensuring the success of future lunar missions.

However, a major challenge to realizing this vision of collaborative lunar exploration is ensuring interoperability between DT systems. Interoperable DT systems require more than just extensible taxonomies and ontologies for data, model, and process exchanges. These systems must enable real-time interactions across distributed and heterogeneous DT platforms, while also addressing concerns around intellectual property (IP) protection. While organizations may be open to others using their components or subsystems, they often hesitate to share proprietary details. Therefore, interoperable DT systems must not only ensure seamless integration but also support ownership rights and enforce IP protection in accordance with the policies and permissions of the IP owners.

In this paper, we present a proof-of-concept development for standards-based interoperability between distributed and heterogeneous DT systems in the context of lunar exploration. We describe the platforms used to prototype digital twins for lunar missions and introduce the emerging Spatial Web standard, currently under review, that facilitates interoperability between these systems. Through testing with selected use cases, we validate the feasibility of real-time collaboration between interoperable DT systems by leveraging the IEEE Spatial Web standard as the interface exchange protocol. Our key contribution is the proposal and demonstration of a standards-based approach that enables collaborative lunar exploration across distributed and disparate digital twin systems, developed by various organizations and nations.

2. LUNAR DIGITAL TWIN SIMULATION AND TESTING PLATFORMS

The long-term objective of our team is to develop the Virtual Environment for Collaborative Lunar Explorations (VIRCLE) [3]. As illustrated in Figure 1, VIRCLE is designed to offer a shareable, standards-based, high-fidelity, physics-driven model of lunar terrains. This platform enables global partners to collaboratively design and test lunar missions in a unified ecosystem, leveraging standardized tools and high-performance streaming infrastructure. The primary goal of VIRCLE is to empower organizations and nations worldwide to build their own digital twin (DT) systems, which can seamlessly integrate into this collaborative framework through open standards. By fostering a loosely coupled, Internet-like architecture, VIRCLE facilitates the exchange of data, models, tools, and processes, ultimately creating a marketplace for DT products and services. This marketplace is envisioned to accelerate the development of a future lunar economy by promoting the reuse of resources and reducing isolated, "stovepiped" DT systems.

At a recent Digital Twin for Cislunar Exploration Workshop hosted by JPL [4], over 30 distinct DT systems were identified among the 200 participants, underscoring the urgent need to minimize redundancy and enhance collaboration within the lunar exploration community. This proof-of-concept project for digital twin interoperability represents a significant milestone in realizing the vision of VIRCLE as a shared virtual environment for collaborative lunar exploration.

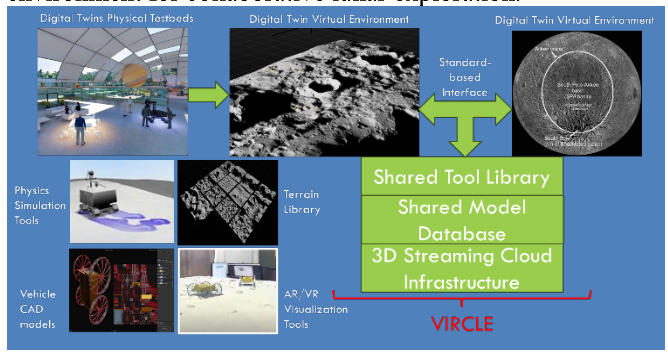

Figure 1 VIRCLE Environment

2.1 Interoperability

Many organizations have developed lunar digital twins (DTs), each tailored to specific mission objectives. However, these systems often remain siloed and inaccessible to others. As the lunar exploration race expands with more nations and private entities participating, the need for enhanced cross-national collaboration becomes critical. Developing a single, unified simulator for all stakeholders is impractical due to the substantial costs in time and resources. Additionally, organizations are protective of their proprietary systems, making them reluctant to switch or share platforms. While shared platforms are vital for achieving interoperability, this capability remains underdeveloped. Most DT systems were not initially designed with integration in mind, and external developers rarely have access to the tools needed to implement cross-platform collaboration. If a universal physics simulator is not feasible, alternative approaches to fostering collaboration and interoperability must be explored.

Enabling digital twin systems to interoperate requires addressing several key challenges across technical, organizational, and policy domains [5]. Developing open standards and protocols for data exchange is critical to ensure that different systems can communicate seamlessly. Achieving semantic interoperability—through the creation of common ontologies—ensures that shared data is interpreted consistently across platforms. Harmonizing models and simulation tools are necessary to enable diverse DTs to interact without compatibility issues. Security and data privacy concerns must also be addressed when sharing proprietary models and data across organizations and countries.

Further technical challenges include real-time synchronization and scalability, particularly in distributed environments. Implementing robust version control and lifecycle management systems ensures consistency as models evolve. Cross-domain integration poses additional challenges, requiring the development of interoperability bridges between systems from different sectors. Establishing clear governance and legal frameworks is essential for protecting intellectual property and defining collaboration terms. Standardized APIs and user interfaces can streamline cross-platform interactions, fostering a fully interoperable DT ecosystem that accelerates collaboration and innovation.

2.2 Standards and Emerging Technologies

Several standards organizations and consortia, including ISO [6], IEEE, and the Digital Twin Consortium [7], have been working to address these challenges. Various digital twin (DT) modeling languages have emerged, such as Microsoft's Digital Twins Definition Language (DTDL) [8], Building Information Modeling (BIM) for the construction industry, and the Asset Administration Shell (AAS) for Industry 4.0. The forthcoming IEEE P2874 Spatial Web standard is poised to significantly enhance digital twin frameworks by enabling property and relationship graph modeling, while integrating extended reality (XR) capabilities backed by AI agents.

Our project focuses on developing proof-of-concept demonstrations showcasing interoperability between existing DT systems, leveraging the Spatial Web standard. Many systems within the lunar DT community rely on 3D engines like Omniverse [9], Unity [10], and Unreal Engine [11], and use a variety of physics simulation tools such as Nastran, Omni-Physics, Chaos Physics, and PhysX. One of the significant challenges we face is achieving real-time integration of these physics simulations with the 3D engines, ensuring accurate, synchronized behavior in dynamic virtual environments.

2.2.1 Nvidia Omniverse

The NVIDIA Omniverse platform includes a range of tools tailored for detailed simulations and visualizations. Within this platform, Isaac Sim was employed for a portion of our project simulations. This tool offers a versatile 3D environment that supports various functionalities, including vehicle rigging, domain randomization, and the development of bespoke modules. A notable feature of Isaac Sim is its ability to integrate smoothly with design applications such as Autodesk Fusion 360, facilitating the incorporation of intricate 3D models into simulations. Powered by NVIDIA's PhysX engine, Isaac Sim provides precise real-time physics simulations. Additionally, its comprehensive Python scripting support enables detailed control over object attributes and the automation of simulation tasks, enhancing both the adaptability and efficiency required for complex project workflows.

2.2.2 Unity

Unity is a widely adopted real-time 3D development platform, recognized for its adaptability and capacity to scale across various industries. Originally designed for video game creation, it has expanded its capabilities to support a wide range of interactive applications, including simulations, virtual reality (VR), augmented reality (AR), and more. The platform's user-friendly interface facilitates rapid prototyping, enabling developers to quickly refine and evolve their designs. Additionally, Unity's asset store and vibrant developer community contribute a wealth of resources that enhance its functionality, offering custom tools and assets for diverse needs. With its ability to support multiple platforms and scale effectively, Unity is widely used in fields ranging from entertainment to engineering to create engaging and visually appealing environments.

2.2.3 Unreal Engine

Unreal Engine, developed by Epic Games, is a robust 3D creation tool that began as a game development platform but has since found applications across various sectors including film, architecture, and virtual production. It is celebrated for its superior real-time graphics rendering capabilities. The integration of the Chaos Physics engine enables high-quality simulations and realistic virtual environments. Furthermore, Unreal Engine provides a versatile setting for developing interactive experiences, facilitating the construction of intricate virtual worlds. The engine's visual scripting system, Blueprint, simplifies the creation of complex interactions without the need for traditional coding, making it an effective solution for a broad range of uses such as gaming, simulations, and immersive VR/AR projects.

2.3 Graphics Format

The Universal Scene Description (USD) [12] format is a flexible, open-source 3D scene description and interchange framework developed by Pixar. USD supports complex scenes with geometry, shading, lighting, and animation, enabling non-destructive collaboration by allowing multiple users to work on different parts of a scene simultaneously. Widely adopted across industries such as visual effects, gaming, and virtual production, USD promotes interoperability between tools and platforms like Omniverse, Unity, and Unreal Engine.

While NVIDIA Omniverse natively uses USD, Unreal Engine supports USD through a plug-in, enabling real-time interactions with USD files. Unity, on the other hand, offers USD SDK support primarily for import/export purposes, but lacks real-time interaction capabilities and robust scene graph support. Our project selected Omniverse and Unity to evaluate the maturity of USD as a common interoperable format across platforms. Integrating physics engines such as OmniPhysics, PhysX, and Chaos Physics across these platforms requires careful tuning and sometimes custom scripting to achieve consistent results.

In real-time collaboration, physics solvers can become bottlenecks due to the time required for simulation. Our team demonstrated that by training a Physics-Informed Neural Network (PINN) model, we could reduce response time from hours to milliseconds [13]. Future research will focus on developing a set of PINN models to further enable real-time collaboration between DT systems.

3. SPATIAL WEB TECHNOLOGY

The Spatial Web merges the physical and virtual worlds, transcending geographic and national boundaries to create a global commons for expression and imagination. This convergence, enabled by decentralizing technologies, artificial intelligence, autonomous vehicles, robots, and the Internet of Things, heralds a new era of interconnectedness. The Spatial Web is built on the foundations of the Internet. The Spatial Web, including the Hyperspatial Modeling Language (HSML) and the Hyperspatial Transaction Protocol (HSTP), creates a seamless digital-physical reality, leveraging augmented and virtual reality and integrating shared values such as privacy, data ownership, and autonomy by design. The Spatial Web is an ecosystem of interoperable, autonomous AI agents based on open standards including HSML and HSTP. The full specification is developed by the Spatial Web Foundation [14] and the IEEE P2874 Spatial Web, Architecture and Governance Working Group [15].

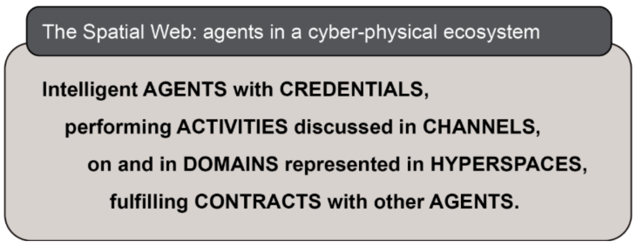

Figure 2 foundational concepts of the Spatial Web

3.1 Spatial Web Concept

The Spatial Web Protocol, Architecture and Governance specification defines the Spatial Web system design by specifying requirements for interoperability and governance of cyber-physical systems at global scale, including autonomous devices, applications, spatial content and operations. Networked communications systems constructed to meet these requirements enable representation of all statements and interactions of the physically oriented, socially-constructed world to be universally represented in a way that makes them amenable to computational modeling and, where applicable, simulation and automation. The system design includes:

● a shared and linkable knowledge domain architecture ("Architecture"),
● a common language with which to describe domain elements and their interrelationships,
● a method for querying and updating the states of those elements ("Protocol"), and
● the ability to allow access and control of that method ("Governance").

Collectively these elements are the Spatial Web Standards. The present specification is comprehensive, encompassing an entire, emerging ecosystem and reflecting trends and needs that drive its development, including but not limited to:
● the increasingly graph-like nature of global data,
● the opportunity for autonomic activities using context-aware, cognitive AI,
● the need for composable systems and applications including the governance of such systems,
● the intrinsic need for secure transactions,
● the rise of machine learning, neural network computation, and edge computing,
● the need for explainable AI and robotic governance, and
● the rise of Digital Twins, IoT and sensor meshes.

The Spatial Web specification provides a reference model composed of three viewpoints: 1) Value for stakeholders, 2) Knowledge model, and 3) Distributed computing.
The viewpoints include requirements on components of the Spatial Web system. The concepts and requirements of the reference model guide subsequent development of Spatial Web Implementation standards and domain-specific Spatial Web architectures. The Spatial Web specification applies an architectural design approach to the Spatial Web System. Requirements are identified by examining stakeholder perspectives and application scenarios. As a result of design synthesis, architecture components are identified as:
● Hyperspatial Modeling Language (HSML),
● Hyperspatial Transaction Protocol (HSTP),
● Universal Domain Graph (UDG),
● Spatial Web Governance,
● Domain-specific Architectures, and
● Autonomous Intelligent Systems (AIS) Rating System.

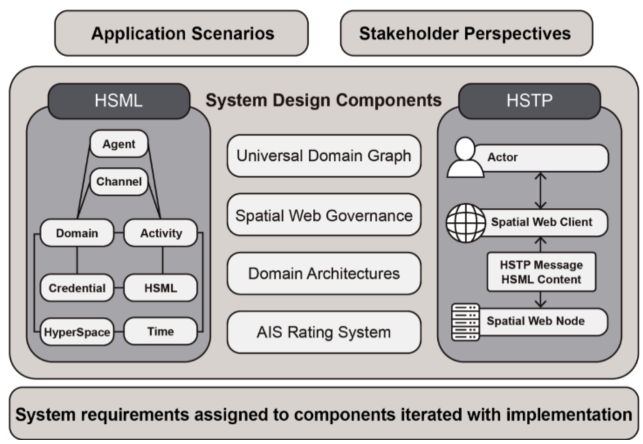

Figure 3 System engineering of the Spatial Web

3.2 Guiding principles

The Spatial Web is guided by these principles: **Spatiality:** Representing information as locations and relations in hyperspace with well-defined metrics enables cognitive computing to be performed based on context. **Ownership:** Users can own their data and digital property and choose with whom they share this data. Moreover, they can retain control of it when they leave a given service provider. **Security:** Secure data collection, transmission, and storage enables interactions and transactions with virtual and physical assets between any user within and across any space; physical or virtual.
Privacy: Individual control, trust, and security utilizing cryptographically secured and decentrally-stored digital identity enables "trustless" complete interactions and transactions with anonymity and auditability. **Trust:** Trust is based on reliable real-time, permission-driven validation of all users, assets, and spaces and their interactions with certifiable and verifiable records that validate various

proofs of ownership, activity, traceability, and rights. **Interoperability:** Searchability, viewability, interaction, transaction, and transportation of asset or user within or across any spaces. Seamless user navigation and asset transfer within and between spaces across devices, operating systems, and locations.
Responsibility: Creating technology in a manner guided by upholding ethical principles of inclusivity, transparency, and cooperation to create a better world for all humanity. **Governance:** Governance is facilitated by the nested structure of domains; Domain Authorities which define norms and laws for a domain; and clearly communicated contracts.

3.3 Space, time, and hyperspace

The term 'hyperspace' is used to capture a generalized concept of space, in an acknowledgment that not only do Euclidean and geographic spaces have spatial structure, but also many other, more abstract data types. These spaces and types can be combined to form complex spaces that can be navigated. The concept of hyperspace is derived from category theory, from which it inherits its compositionality, and is fundamental for the Spatial Web. Figure 4 provides a summary of the various classes of hyperspace.

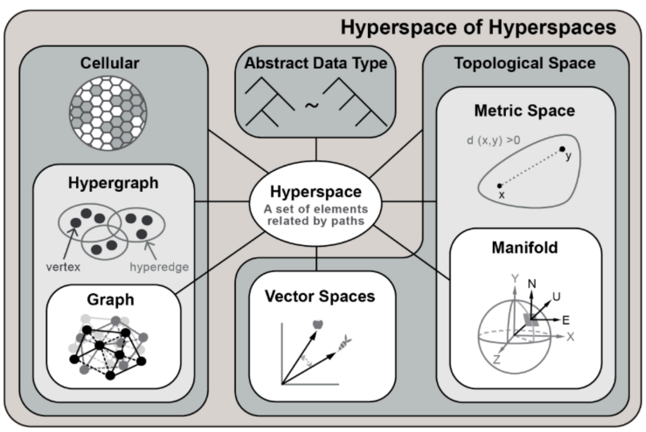

Figure 4 Basic classes of hyperspace.

3.4 Spatial Web Ontology

The Spatial Web ontology is composed of Entities that are the primary concepts used across the Spatial Web in HSML. HSML implements the Spatial Web ontology as a set of schemas that enable increased coherence across diverse datasets without sacrificing flexibility. The Spatial Web ontology (Figure 5) defines several classes. All classes are types of the Entity base class. The Spatial Web ontology builds upon several existing ontologies, i.e., IEEE 7007-2021 [16], ISO/IEC 21838-1:2021 [17], Suggested Upper Merged Ontology (SUMO) [18]

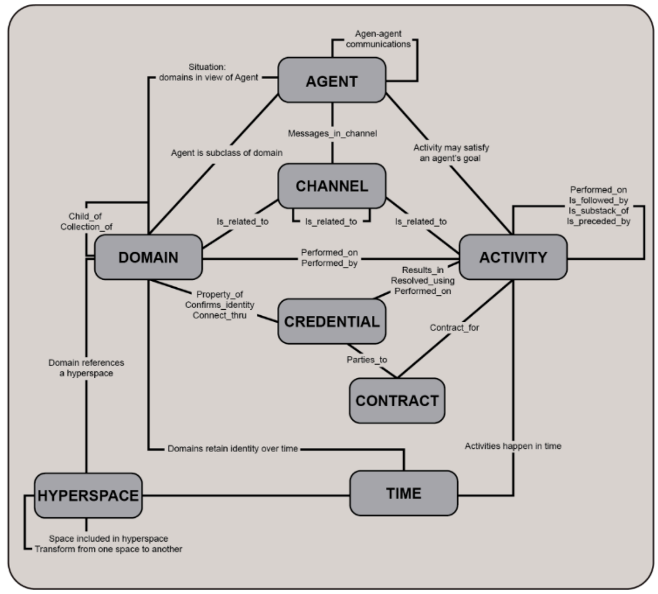

Figure 5 Spatial Web entity relationship diagram.

3.5 VERSES Technology

VERSES Inc is an AI company [19] developing technology and tools built on top of the Spatial Web standards. This project utilized VERSES Genius Core to store data in the HSML format. HSTP was used to register HSML entities, make updates and query their data.

4. DIGITAL TWIN INTEROPERABILITY DEMONSTRATION

To conduct interoperability demonstration for this project, we selected a test scenario involving a rover disembarking from a lander in the lunar south pole environment. The goal was to evaluate the interoperability between DT models and different platforms. As depicted in Figure 6, the team created a detailed lunar terrain model, along with 3D CAD models of the rover and lander, for testing across distributed and diverse DT systems.

Figure 6 Interoperability Test Scenario

4.1 Lunar Terrain Model Creation
For our lunar terrain simulation, we utilized data from the Lunar Reconnaissance Orbiter (LRO) to generate high-precision height maps of the Moon's surface. By leveraging the Digital Elevation Models (DEMs) from LRO, we extracted elevation data at a resolution of 5 meters per pixel, converting it into an 8-bit grayscale height map where each pixel's value represented a specific elevation in meters. This allowed us to produce a detailed grid of height values and generate a fully interactive 3D model of the lunar terrain, accurately capturing surface features and elevations. The resulting model provides a highly realistic environment for simulation and exploration, closely reflecting the lunar surface conditions.

However, the fidelity of this terrain is inherently limited by the resolution of the available satellite data. Without access to higher-resolution data, creating more accurate terrain remains a challenge for DT simulations. We addressed this limitation by applying displacement techniques and scaling large areas of the lunar surface, leveraging the Moon's relative surface homogeneity. By layering crater formations at varying strengths and orientations, we achieved a natural representation of lunar impact events. This methodology allowed us to generate a versatile set of lunar terrain tiles, combining real-world data with artistic renderings to simulate dynamic mission scenarios effectively.

4.2 Develop 3D CAD Models
The NASA Cooperative Autonomous Distributed Robotic Exploration (CADRE) rover [20] model was used in this project. The rover's base geometry was modeled using Fusion 360, simplifying the design to include only essential components such as the chassis and drive system, while maintaining visual integrity. The outer surfaces were flattened into a 2D plane using 3DS Max to facilitate texture mapping, and textures were applied through Adobe Substance Painter. A process known as "baking" was used to define light interactions on the surfaces, enhancing realism without taxing computational resources.

For movement simulation, the rover meshes were imported into Omniverse, where Signed-Distance-Field meshes were assigned to establish complex collision fields. Rigid body physics and lunar gravity (1.62 m/s²) were applied to the scene, allowing realistic movement interactions. The rover's wheels were controlled through angular drive physics, with constraints limiting the top speed to 0.4 m/s. Manual control was implemented through an Omniverse action graph, while Python scripting enabled autonomous navigation based on a series of waypoints. This primitive control system followed a feedback loop but lacked advanced capabilities such as obstacle avoidance, which will be integrated in future iterations.

4.3 Physical Prototype Validation
Lunar exploration entails the deployment of complex robotic systems that interact with geological features under the lunar regolith, often encountering unpredictable conditions. Our research focuses on simulating these interactions using multiple DT models. Given the inherent uncertainties within each model, achieving accurate simulation results is challenging without rigorous validation. To address this, we developed a set of physical prototypes of the lunar terrains to validate our simulations within a digital twin framework. As shown in Figure 7, the virtual test environment featured a digital twin model of the rover alongside a physical prototype of the lunar terrain. The prototype was constructed using polyurethane foam with a density of 12 pounds per cubic foot, offering both structural integrity and precision for model testing.

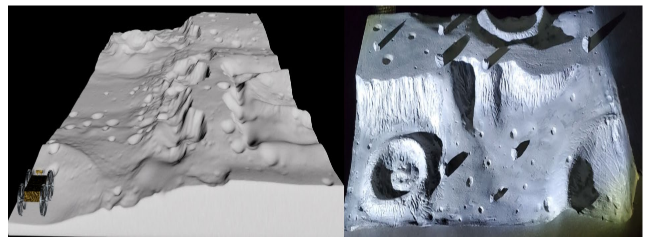

Figure 7 Digital Twin Virtual Test Environment (left) and Lunar Terrain Physical Prototype

4.4 Interoperability Demonstration
The primary objective of this proof-of-concept project was to demonstrate the feasibility of real-time collaboration using a standard-based spatial web protocol. We aimed to assess the possibility of interactive collaboration across distributed systems and varying 3D engines, while addressing concerns about intellectual property protection.

4.4.1 Distributed Real-Time Collaboration Demonstration
In this demonstration, we demonstrated real-time collaboration between distributed digital twin (DT) systems over the Internet. As shown in Figure 8, a DT system based on NVIDIA Omniverse at JPL was able to interact with another Omniverse system at CSUN, exchanging messages via the HSML protocol. A critical factor for real-time collaboration is the frame rate at which movement is rendered. Omniverse, being resource-intensive, can experience fluctuating frame rates depending on the system's performance. Under typical conditions, a frame rate of 60 fps is achievable, but as the simulation complexity increases, the frame rate may decrease. To ensure smooth real-time collaboration, we maintained a minimum frame rate of 30 fps during data transfer, ensuring that each game object's position and rotation were updated 30 times per second when in motion. This choice aligns with the animation industry's standard minimum of 24 fps, and 30 fps is widely supported across monitors.

Latency is a pivotal factor in real-time collaboration. In distributed digital twin (DT) collaborations, excessive latency can lead to noticeable delays between actions and result in desynchronization between the visual display and the actual events occurring within the simulation. Drawing from video gaming standards, we aimed for a latency range of 40-60 ms. Although the latency fluctuated at different stages of the project, it typically remained below 50 ms. This consistency helped ensure seamless interactions between the systems, maintaining a fluid and responsive collaborative environment.

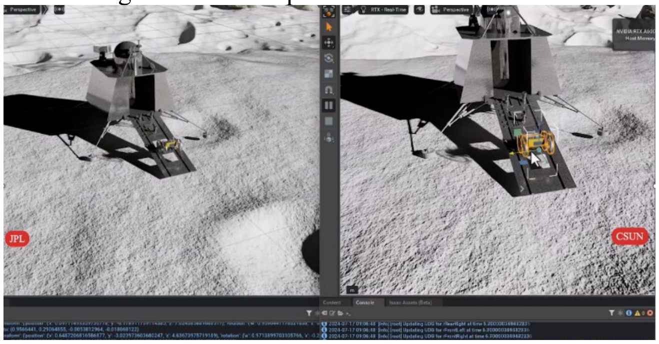

Figure 8 Distributed Collaborations

4.4.2 Collaboration Between Heterogeneous Systems Demonstration

We also demonstrated real-time collaboration between DT systems using different 3D engines. As illustrated in Figure 9, we selected Omniverse and Unity to test interoperability, with communication facilitated through the HSML protocol. A key challenge was managing the different coordinate systems used by each engine—Unity employs a left-handed system, while Omniverse uses a right-handed one. To standardize data exchange, we opted for the right-handed coordinate system, requiring matrix multiplication on incoming data from Unity to account for inverted Y and Z values. This adjustment was necessary not only for positional data but also for rotations, due to the nature of quaternions.

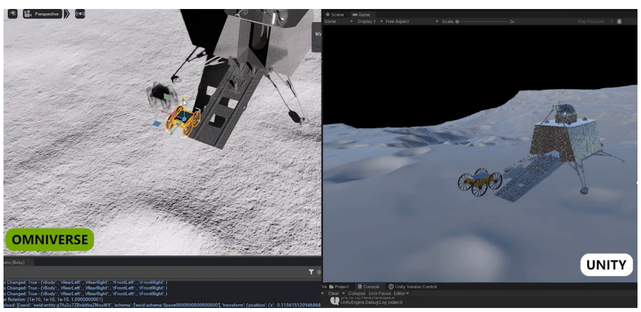

Figure 9 Collaborations Across Omniverse and Unity

4.4.3 Remote Execution IP Protection Demonstration

This demonstration focused on intellectual property protection by
integrating a proprietary sensitive module critical to the simulation on a remote system to test the possibility of different users using it without accessing the code or introducing delays in the simulation.

This module here represents the results of a previous study performed by our team to speed up classic simulations of rover motion on the Moon regolith. This is usually a bottleneck for accurate, and in real-time, simulations as the physical interactions of the rovers' wheels, or tracks, with Moon regolith are very complex. Due to its very special environment (absence of atmosphere, erosion etc), the Moon soil, or regolith, behaves very differently from any other terrain on Earth. For example, the rovers' wheels sink very differently on this regolith than on Earth [21]. It is thus very challenging to accurately predict the position of the rovers on the Moon at any given time. Classical simulations usually use finite element analysis based on Terramechanics research and, although they manage to achieve very accurate results, they usually run much slower than real-time (50 to 10,000 times slower) even when using high-end GPUs like A100. Our novel approach uses Physics Informed Machine Learning (PIML) [22] combining ordinary differentiable equations (ODEs) with a neural network trained to reduce the differences between the solutions of the ODEs and the observed ground truth positions of the rovers' wheels. This difference, very complex to capture with physical laws, is thus learned by a neural network. The first results prove that this novel approach can predict very well the motions of rovers even on regolith while reducing the run time from 1.5h to under 150ms. This module is thus a good example of a new capability that companies could provide in a more global simulation but would want to protect their intellectual property of.

In order to use this novel capability without sharing the code and protect intellectual property, this PIML module was stored on a remote machine. Then, using the HSML protocol, other software can use this external module to accurately predict the rover's position or its ability to traverse a slope for instance and get the output in real time to then perform planning or decision-making actions. As depicted in Figure 10, the DT system retrieved the results of the remote PIML module through HSML message exchanges, ensuring the protection of proprietary physics models while maintaining real-time feedback.

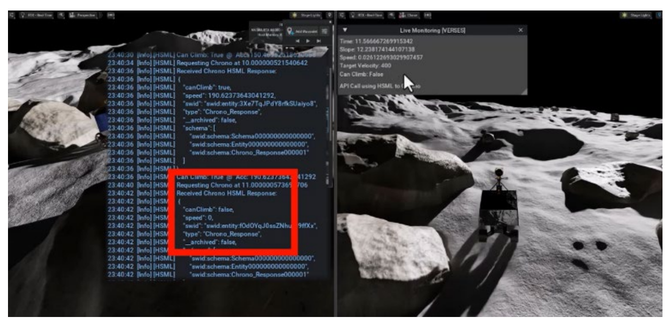

Figure 10 Remote Physics Calculations

5. CONCLUSIONS

This paper presents the results of a proof-of-concept project that demonstrated the feasibility of using a standards-based Spatial Web protocol to enable real-time collaboration between distributed and heterogeneous DT systems. We constructed a DT system using NVIDIA Omniverse and shared lunar terrain data with Unity. Through interoperability demonstration, we successfully conducted real-time collaboration across distributed systems, interoperability between Omniverse and Unity, and remote execution of a PINN physics model, with results integrated back into a USD-based system. Our demonstration confirmed the viability of achieving seamless, real-time interaction between distributed and disparate DT systems.

Future work will focus on developing an open-source implementation of an interoperable DT environment using the Spatial Web standard. In alignment with the VIRCLE vision, this environment will serve the lunar exploration community, enabling the sharing of data and models to accelerate the development of a future lunar economy.

ACKNOWLEDGMENTS

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration (NASA, 80NM0018D0004), and partially supported by NASA MUREP Institutional Research Opportunity (MIRO) (80NSSC19M0200) and MUREP High Volume (80NSSC22M0132). We acknowledge Prof. Nhut Ho's resource support from California State University Northridge's Autonomy Research Center for STEAHM (ARCS).

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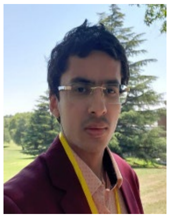
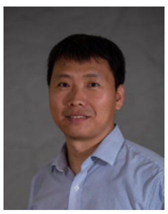
BIOGRAPHY

Jared Carrillo is a mechatronics engineer with a focus in robotics and machine learning. His research at CSUN has been focused on gauging current usability with AI enhanced assistive tech. At JPL, he was tasked with project integration and collaboration.

Rayyan Mridha is a computer science student at Northeastern University interested in software development and AI. At JPL, he created scripts to improve the moonwalker simulation and worked with VERSES AI to implement interoperability. He has also researched the Spatial Web standard that would allow for collaboration through HSML queries on various platforms.



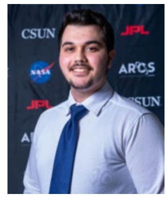
Subhobrata is a Research Assistant at California State University, Northridge (CSUN), where his research centers on robotic perception, navigation, and mapping in both single and multi-agent systems. He is currently developing a robust multi-agent system that will evolve into a fully operational digital twin. His interests also encompass creating interactive and modular digital twins for space systems.



Bingbing Li is an Associate Professor of Manufacturing Systems Engineering at California State University Northridge. He also serves as the Associate Director of NASA Autonomy Research Center for STEAHM (ARCS), Co-Director of DOE Industrial Assessment Center (IAC) at University of California Irvine and California State University Northridge (SMART IAC). Hs research focus has been in additive manufacturing, smart manufacturing, and environmental sustainability. He received his Ph.D. degree in Industrial Engineering from Texas Tech University in 2012.

Nhut Ho is a Professor of Mechanical Engineering at CSUN. As the Founding Director of the NASA-sponsored Autonomy Research Center for STEAHM (ARCS), he provides intellectual leadership to 30+ multidisciplinary professors conducting autonomy-related research with collaborators from NASA centers and diverse industries, including aerospace, waste management, manufacturing and construction, healthcare, and AI. He received his Ph.D. degree from MIT in 2004 with a focus on designing automation for complex systems.

Elliott Sadler is a Mechanical Engineer with a focus on manufacturing, product design, and project management. Never afraid to take on a new project or challenge, Elliot has formed a career around servant leadership, working with many teams over the years to achieve goals ranging from k-12 summer camps to digital simulations of real-world systems.



Neville Elieh Janvisloo is a senior undergraduate student studying computer science at California State University Northridge (CSUN) with a passion for artificial intelligence and computer vision. His research at CSUN has been focused on implementing transformative technologies by leveraging data from intricate systems. At JPL, he created a path planner in charge of safely navigating multiple rovers on the moon using terrain data and satellite imagery.

Gautier Bardi de Fourtou is an Aerospace Engineer with a specialization in artificial intelligence acquired through a second Master from School of Mines Paris (Paris, France). His coursework has been focused on machine learning, computer vision, gesture recognition, analysis and prediction. At JPL, he performed research into Physics Informed Machine Learning to help predict the motion of rovers on Moon regolith.

Edward Chow is the Manager of the Civil Program Office at the NASA/JPL. He also served as the project manager/PI/Co-I for a number AI, advanced networking, test & evaluation, and cybersecurity projects. He received his Ph.D. in Electrical Engineering from the University of Southern California in 1988. He is the recipient of the prestigious NASA Exceptional Engineering Achievement Medal and the JPL Lew Allen Award.

Thomas Lu is a Senior Researcher at NASA/JPL. His research focus has been in AI, deep learning, data analysis, multispectral imaging and computer vision areas. He has served as an organizer and organizing committee member of SPIE conferences, edited a book "Advances in Pattern Recognition Research", contributed 3 book chapters, co-authored over 70 journal and conference papers, co-invented 6 patents. Thomas received his Ph.D. degree in Electrical Engineering from the Pennsylvania State University.

George Percivall is a Distinguished Engineering Fellow for the Spatial Web Foundation. Previously, he engineered cyber-physical and information systems for NASA, General Motors, and Hughes Aircraft. He was CTO of the Open Geospatial Consortium. He is a member of the Apache Software Foundation with BS and MS degrees in engineering from the University of Illinois. As principal of GeoRoundtable, he currently leads developments in the IEEE Geoscience and Remote Sensing Society and the IEEE Computer Society.

Capm Petersen is the Chief Innovation Officer and co-founder at VERSES Inc. He specializes in pilot projects that demonstrate the promise of intelligent agents, autonomous systems, and governance, especially in the domains of space exploration, autonomous vehicles and logistics. In addition, he assists in the development and adoption of the IEEE P2874 Spatial Web standards.

Aidin Eslami is a software engineer with 20 years of experience in edge computing, augmented reality (AR), robotics simulation, and IoT. He graduated with a bachelor's degree in software engineering from Ferdowsi University of Mashhad (FUM) in 2004. Throughout his career, Aidin has worked on innovative projects using cutting-edge technology. Currently, at VERSES, he is focusing on autonomous agents, exploring how these agents can collaborate across networks to improve AI system intelligence and efficiency.

Alessandro Muzzi is a dedicated Senior Software Engineer at VERSES, holding a Master's in IT Engineering from the University of Parma. His first assignment was the UAM European project FF2020 and has since developed various tools to leverage R&D findings, including an automated tool for generating multi-platform digital twins from 3D models.

Dr. Jacqueline Hynes is a Research Engineer at VERSES and The Spatial Web Foundation, where she focuses on developing interoperability and governance frameworks for autonomous intelligent systems and multi-agent ecosystems. She previously held the position of Investigator of Neuroscience at Brown University, where her research encompassed visual-motor systems neuroscience, neuroAI, and brain-computer interface technologies. Dr. Hynes has contributed to the development of IEEE standards for Spatial Web technologies.