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LEVERAGING DIGITAL TWINS TO SUPPORT A SUSTAINED HUMAN PRESENCE ON THE LUNAR SURFACE

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ABSTRACT

Having a sustained human presence on the lunar surface is a central objective of the Artemis Program, as it represents a key pre-requisite in resource mining operations on the Moon as well as an important steppingstone for future Martian exploration and colonization. Despite its importance, this endeavor has little precedent to rely on to inform the many challenges it needs to address. Digital Twin, in recent years, has been employed in a wide range of applications. In this paper, we explore its usefulness in establishing the Artemis Base Camp. Digital twins can be applied to various stages of the lifecycle of the lunar base development. We also identify several open questions that need be addressed before the digital twin can be utilized effectively in this project. In fact, addressing these questions could facilitate deploying digital twins in use cases in a wider spectrum of industries and sectors.

1 INTRODUCTION

The Artemis Program is an international collaborative endeavor, led by the National Aeronautics and Space Administration (NASA), to fly robotic and manned missions to the Moon. One of its core objectives is to establish a sustained human presence at the Moon's South Pole that will enable multi-month stays by astronauts to conduct scientific and economic activities on the lunar surface (NASA 2020b). Between 2022 and 2028, four Artemis missions are planned with the goal to establish a Lunar Gateway around the lunar orbit, which can host a four-person crew for multi-month stay as the precursor for lunar landing, tentatively planned in 2029. The lunar landing will be accompanied by the establishment of a permanent installation, known as the Artemis Base Camp. Besides being a base of operations for scientific research and resource mining, the base camp will also serve as a technology testbed and waystation to realizing NASA's plan for a human mission to Mars in the 2030s.

According to NASA's Plan for Sustained Lunar Exploration and Development, the Artemis Base Camp consists of three main constituent elements: 1) A Lunar Foundation Surface Habitat (LFSH) to house up to four crew members and sustain them for multi-month surface stays; 2) a lunar terrain vehicle (LTV) to transport the crew between the landing zone and the LFSH; and 3) a Habitable Mobility Platform to enable extended mobility for the crew to venture out across the lunar surface for up to 45 days. Supporting the base camp, the Lunar Gateway in orbit will serve as a short-term habitation module, communications hub, and holding area for robotic equipment (Jackson 2018).

Designing, building, operating, and maintaining this lunar-surface habitation ecosystem is an unprecedented, multi-domain, multi-disciplinary, and multi-national endeavor. In addition to the myriad scientific disciplines involved, making it an equitable enterprise requires a range of knowledge domains such as power systems, autonomous manufacturing, mining and excavation, automation, resource optimization, system interoperability, supply chains, telecommunication and navigation, space vehicles,

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etc. Furthermore, as the Artemis Program has the participation of two dozen countries, it is essential to establish a framework of governance that coordinates activities undertaken by individual participants, implements and enforces sensible policy, regulation, and laws, and ensures equitable distribution of all gained knowledge and resources from the Program.

Modeling and simulation (M&S) is an indispensable tool that underpins these diverse considerations to bring about a successful mission outcome. These considerations are interconnected, and the system dynamics that emerge from the scale and complexity of Artemis are unpredictable and have hidden, higher-order effects that impact mission efficacy. To minimize risks across all stages of the Program, a holistic approach is needed to not only develop the robust infrastructure that can withstand the extreme conditions on the lunar surface, but also perform accurate assessment of a large number of scenarios to anticipate unforeseen situations that may arise, often in real time.

We propose the use of digital twins (DTs) as a viable modeling tool to support the entire life cycle of the Artemis Base Camp, which is characterized by its high degree of complexity (physical environmental, logistical, policy, etc.) and underlying complex dynamic behaviors. In the remainder of this paper, Section 2 discusses some of the problems concerning a sustained habitation ecosystem. Section 3 introduces DTs as a whole-of-the-lifecycle modeling paradigm to support the establishment of the Artemis Base Camp, from concept to operation, and discusses how digital twins may be leveraged to address the technical, operational, and policy considerations associated with it. While there are certainly benefits to adopt digital twins, Section 4 also presents several challenges DTs need to overcome to make it a viable solution. Section 5 concludes the paper.

2 LUNAR SURFACE: A CHALLENGING LANDSCAPE

In this section, we discuss a number of considerations when building and maintaining a sustained human habitat on the lunar surface. The Moon is ripe with many risks, which include environmental (Cohen 2002), extreme access, logistics, transportation, autonomous robotics, and policy development, to name but a few.

2.1 Environmental Hazards

Several harsh environmental challenges are being addressed by the lunar surface research community. Radiation poses a risk that would lead to significant health impacts to the habitat occupants, given its high levels on the surface. On Earth, human exposure to radiation is 1 microSievert per year (µSv/yr), while on the lunar surface the radiation exposure may be as high as 1,369 µSv/yr (Zhang et al. 2020). Shielding astronauts from radiation is crucial before long-term human presence is possible on the lunar surface. One proposal that offers a potential solution is using lunar regolith or lava tubes, as they have proven quite effective at blocking radiation (Naito et al. 2020; Akisheva and Gourinat 2021).

Lunar dust is another danger affecting the well-being and operations of humans and equipment (Stubb et al. 2005). The lunar surface experiences a steady flux of micrometeoroids of various sizes and density, which creates a potential of impact and collision with mechanical and electrical systems, not to mention the life-threatening risk it presents to the astronauts. Indeed, the Apollo astronauts have all reported issues regarding the finely grained (i.e., an average grain size of approximately 70µm), electrically charged dust can lead to reduced vision and difficulty in breathing, as well as interfering with the abrasion and adhesive properties in the equipment. Using habitats such as lava tubes would not only protect against radiation, as aforementioned, but could also provide shielding against micrometeorites (Sauro et al. 2020).

Several other environmental hazards on the lunar surface also need be taken into consideration. Vacuum on the Moon is near absolute, which can affect the operations of the habitats (e.g., inflatable habitats need to account for changes in pressure and temperature). Gravity is reduced to one-sixth of that on Earth, which can affect habitation, crew mobility, and the equipment that could become more top-heavy. Reduced gravity could also make mining operations more difficult to implement. Furthermore, the Moon has a 28-day diurnal cycle, resulting in extreme changes in temperature and lighting. The cycle alternates between 14 days of daylight in scorching heat, and 14 days of darkness and freezing temperatures. The extremities could impact the physiology and psychology of the astronauts, whereas the infrastructure has to continuously endure and sustain such drastic changes.

2.2 Extreme Access

Extreme access aims to develop and leverage capabilities that enable the effective and efficient navigation, exploration, and access of steep and uneven terrain on the Moon. Critical and essential resources such as water and volatiles, which are needed for life support and fuel production, and are located in Permanently Shadowed Regions (Stubb et al. 2005; Crawford 2015), can be difficult to access and mine. This brings power and extreme temperature to the forefront of challenges to resolve before mining in-situ resources becomes possible, a key milestone to implementing life-support systems. Moreover, communication with the surface can be challenging and will need full consideration moving forward.

Both challenges are actively being addressed today, although it is important to understand how potential solutions can influence the outcome of establishing sustained presence on the Moon. To support the extreme-access needs for NASA’s Plan for Sustained Lunar Exploration and Development, Lordos et al. at MIT developed a robot for mobility in different terrains and is equipped with a small set of simple tools (Lordos et al. 2022). These Walking Oligomeric Robotic Mobility Systems (WORMS) are designed to be modular and can be field configured by non-specialists to traverse difficult surface contours. At the time of their paper’s publication in 2022, the WORMS researchers have built a proof-of-concept prototype of a first-generation WORM system, which is yet to be tested and evaluated for its mission readiness.

2.3 Logistics, Economics, and Mined Resources

Logistics for supplying and operating the Artemis Base Camp is a daunting task, as it requires establishing a robust infrastructure such as power systems, communications, radiation shielding, a landing pad, waste disposal, and storage planning (NASA 2020). Much of the material in the construction of the Base Camp will be delivered from Earth, where it is sourced to different international vendors. Efficient management of logistics requires the collaboration and coordination between international partners to establish standards in component manufacturing for interoperability, and to avoid duplication of efforts. Failure to do so would lead to unsustainable capabilities, a degraded system maintenance regime, and ballooning mission costs.

The economics of building and operating the Artemis Base Camp can directly impact the willingness of participating countries to contribute to the program, and therefore needs to be carefully analyzed. Some aspects of such economics are directly measurable, such as facility construction, energy consumption, crew and material delivery, payload systems, etc. Others can be estimated, such as In-Situ Resource Utilization (ISRU), impact of supply-chain disruption, integration of new technologies and capabilities, etc. It is desirable to utilize locally mined resources to make base camp operations more sustainable. Initially, the investment for exploring and mining the regolith is likely to be substantial. An analysis of the payoff versus the investment is necessary to ensure an equitable outcome of the endeavor. This trade space can be evaluated via simulation, modeling and data analysis tools, and can provide a means to reduce the overall cost and improve the speed in implementation.

2.4 Transportation Planning

Two of the three main components of the Artemis Base Camp, the LTV and habitable mobility platform, are tasked with transporting crew and equipment for various tasks across the lunar surface. Transportation, be it between the landing pad and the LFSH or for mission sojourns, requires meticulous planning that takes into factors such as surface temperature, power consumption, freight weight, terrain, communication, and mission duration (in the case of the habitable mobility platform). Another aspect of lunar surface transportation is to transport people, resources, supplies, and payload systems between the Moon and Earth. It is easier to launch from the Moon than from Earth due to lower lunar gravity. While the lack of a lunar atmosphere means there is no drag to the spacecraft, aerobraking is not possible, thus requiring extra fuel for the spacecraft to land. Simulation and analysis could help devise an optimal strategy to execute safe and efficient transport maneuvers.

In the long run, we envision the lunar base to expand to include additional landing sites and habitats. Such expansion would inevitably lead to growing traffic between landing sites and bases, between bases, and between the base and mining sites. Railways have been envisioned to connect different nodes of the lunar community to facilitate crew and goods transport. One idea being explored is the use of magnetic levitation (MagLev) to for the lunar railways, since the lack of atmosphere would potentially allow the MagLev trains to travel at speeds comparable to aircraft on Earth (Schaler 2021). On the other hand, the train cars need be individually sealed and equipped with their own life-support systems and must be designed to prevent derailment and potential loss of life. In all likely scenarios, transportation planning will be critical to ensure safe and efficient navigation across the lunar surface.

2.5 Autonomous Robotics

Part of the Artemis Program’s mandate is to test and deploy new technologies that can be used on the lunar surface, as well as the Moon to Mars initiative (NASA 2020). Given the resource and manpower constraints, advanced autonomous robotics will play a critical role in the management and operations of the Artemis Base Camp. Greater use of autonomous robotics enables a robust, efficient, cooperative, and sustainable ecosystem in a harsh and alien environment, as an integral part of autonomous planetary missions. Samid et al. (2008) applied simulation to study employing infrastructure robotics to automate many tasks in ISRU, construction, and maintenance. For example, excavation often consists of repetitive tasks, a viable use case for automation. The paper also attempted to determine whether further reduction in uncertainty of key variables would be equitable. But at the time of its writing, the only way to assess the equity question was to have precursor exploratory missions, which was not a practical approach.

An autonomy strategy and clear understanding of human input expectations to ensure efficiency of operations in a lunar environment should be performed, for example, via a human-machine teaming model to determine which functions should be autonomous. This includes, but is not limited to, considerations around automated navigation and transportation at the surface, for both astronauts and goods.

2.6 Policy

The following policy areas require consideration for the establishment of a lunar base. Rules, regulations, guidelines at the Moon, and the current Space Law in general should be revised and/ or be developed, including norms of good behavior. Collaboration and coordination of efforts within the government, with industry stakeholders, and with the international community will be a key enabler to a successful establishment of a lunar habitat ecosystem. Current international design and building codes should be examined and options proposed for the harsh lunar environment. Candidate Occupational Safety and Health Administration (OSHA) standards for manufacturing in space could be brought to the international community for coordination and standardization. Understanding the lessons from building in harsh environments on Earth (e.g., Antarctica) should also be explored. Long-term planning for governmental and commercial development should be performed to include transportation planning to inform policies for the movement of people and materials across the lunar surface and community service planning to provide for common services (e.g., water, sewer, recycling) and lunar worker health/habitat emergencies.

3 DIGITAL TWIN MODELS FOR SUSTAINED HUMAN HABITAT

Digital twins can be leveraged to address the challenges presented in Section 2. While several definitions of what a digital twin is have been proposed in the literature (see, e.g., Fuller et al. 2020), this paper follows the conceptual definition developed by Grieves and Vickers (2016). A DT is a virtual representation of a system lifecycle that closely mirrors the state and operational characteristics of said system at relevant points in its lifecycle, for the purpose of optimizing design, development, use, maintenance, and retirement of said system. It is the logical extension of utilizing physical twins throughout human history and moving that use into the digital/virtual realm. The first concept of a DT model was formally introduced in 2002. However, it is only with the explosive growth of digital computing and communications capability in the last decade that DTs are becoming an increasingly viable tool to represent highly complex entities with a high degree of resolution and fidelity.

Figure 1 illustrates the basic concept of how a DT works. A physical system is equipped with a number of sensors that continuously collect live data about the state and functionality of the system. Periodically and frequently, the data is then transmitted to the system's digital twin, located in a computer, which performs analysis and diagnosis to assess its current operation. If it detects some anomaly through the data, the digital twin performs computations to find a remedy. It then sends the remedy back to the physical system, which acts upon it to mitigate the anomaly and restore normalcy to the system performance.

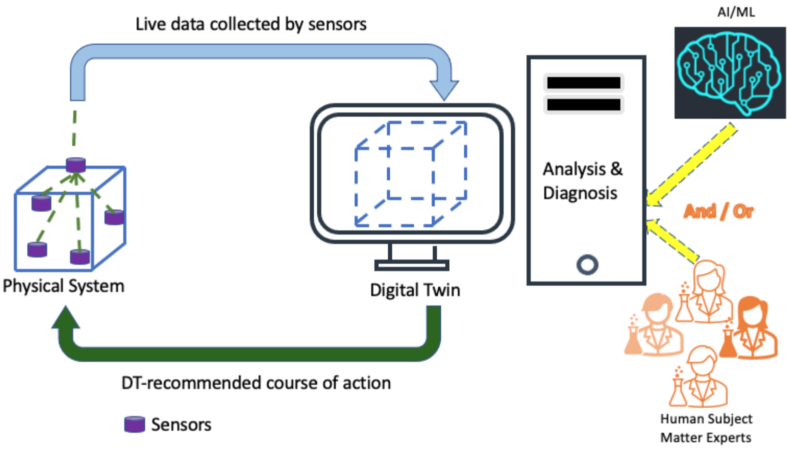

Figure 1: How a digital twin works.

DTs are being applied to an increasingly diverse array of industries, including, but not limited to, advanced manufacturing, smart city, healthcare, automotive, aviation, and supply chain management. What sets it apart from the traditional M&S paradigm is that it can be utilized at all stages of a product or service's lifecycle, from its ideation to the eventual disposal. This continuum is in large part due to the explosive growth of Internet of Things, in which small, inexpensive, and energy-efficient wireless sensors are mass-produced and deployed to a wide range of industrial and commercial products and services for data collection.

At the time of this paper's writing, LTV, one of the three main components of the Artemis Base Camp, is expected to be mission-ready sometime after 2025; both the Habitable Mobility Platform and LFSH remain largely at the conceptual design stage. Below we discuss several use cases to illustrate the usefulness that DTs bring to the continuing development and deployment of the base camp.

3.1 Design of the Artemis Base Camp

The site of Artemis Base Camp, as a permanent habitable output, is planned to be at the lunar South Pole, near the Shackleton Crater (Dunbar 2019). A wealth of knowledge about the site has been accumulated through previous missions. The scientific data will directly inform the design of the LTV, Habitable Mobility Platform, and LFSH, enabling us to develop high-fidelity, high-resolution, physics-based digital twin models of the three components. Additionally, any base camp ecosystem must also include supporting infrastructure such as power grid, landing pads, sewers, and greenhouses (for growing vegetables). In developing these models, historical scientific knowledge, and up-to-date real-time data can be fed into the models, subjecting them to realistic surface conditions in order to evaluate their performance under these harsh conditions. The challenges of environmental hazards and extreme access, as described in Section 2, can be addressed this way. The base camp must have stringent requirements against detrimental effects such as lunar dust erosion, increased radiation, and reduced gravity. We can feed the known knowledge of environmental effects into the models to tweak and refine the models, thus arriving at the best design to meet safety and mission requirements.

Developing these models individually is not enough, as the base camp is a highly complex ecosystem, where individual components are deeply intertwined (e.g., the crew on a sojourn mission in the Habitable Mobility Platform may lead to reduced power consumption at the LFSH). Therefore, a holistic approach to designing lunar habitation ecosystem is essential to reduce risks, optimize resource utilization, and maximize robotics and automation. Here, digital twins have a role to play. Indeed, one of the most successful applications of digital twins has been in the field of urban planning for smart cities, where many works have been published (e.g., Shaharuddin et al. 2022; Yang and Kim 2021). Like a smart city, the Artemis Base Camp can be viewed as a complex, social-technical system of systems that is multi-scale, multi-attribute, and multi-objective. Corrado et al. (2002) proposed a federated approach to applying the digital twins to smart city as such a system of systems where, instead of a single digital twin model encompassing the entire city, a multitude of digital twins that model different components that constitute the city should be developed. In such a federated approach, the models collectively collaborate with each other as a system of systems to contribute to a solution.

The federated approach is equally applicable to the design and development of the Artemis Base Camp. The three main components, supporting infrastructure, and other essential machinery such as autonomous robots come together to form a digital system of systems, allowing researchers and stakeholders to study different configurations of integrating them into an ecosystem. Factors that need be taken into consideration include criteria for landing pads, extreme temperature swings, placement of power source (i.e., continuous sunlight), and easy access to areas of complete darkness that may hold water ice (Shekhtman 2021). As an example, Shekhtman points out that while at a higher elevation, e.g., on crater rims, there are longer periods of sunlight, the bottoms of some deep craters, where water ice is likely held, are often in near perpetual darkness. The digital twins of the base camp can be utilized to study the trade space while designing the base camp. These digital twins could be a viable tool that evaluates this and other factors in order to minimize the risk and maximize the mission success.

3.2 Operations and Maintenance

Operational management at the Artemis Base Camp is critical to ensure the safety of the astronauts and mission success. DTs are well suited to support many tasks such as transportation planning, monitoring environmental hazards, and operating autonomous robots. Three scenarios are discussed here: prescriptive maintenance, human-robot collaboration, and uncovering higher-order adverse effects early on.

The Artemis Base Camp is by design a data-rich environment, where environmental, operational, and biometric systems are constantly monitored, and data from these systems is periodically collected for analysis to ensure the base camp operates safely and efficiently. Such an environment provides ample real-time data input to a digital twin model of the base camp (as a system of systems), which can perform analysis to assess the state of the base camp in real-time or near real-time. When the digital twin possesses both real-time and historical data sets (for baselining purposes), it can perform prescriptive maintenance with the aid of Artificial Intelligence (AI) to uncover the root cause of the degradation and find a solution to rectify the degradation. It then sends the solution back to the base camp to implement the solution on the physical twin.

Base camp operations are envisioned to be highly automated and roboticized, and humans will largely play a supervisory role in many aspects of base operations. The concept of Human-Robot Collaboration (HRC) has been extensively studied in research literature. More recently, Uhlenkamp et al. (2019) discussed a digital twin framework developed for a production system based on HRC. The paper identified a number of considerations of HRC, including dynamic task planning, adaptive robot control, collision avoidance, and unpredictable human behavior. Such considerations are also likely present in the Artemis Base Camp operations. Collaboration between humans and robots they control needs to be well practiced in order to effectively execute various mission tasks. The richness of the data collected would enable the base camp digital twin to serve as a testbed that can explore and analyze the best pairing of humans and robots in a safe and efficient environment.

A well-developed digital twin model can capture second- and third-order effects that may be otherwise overlooked in conventional simulation methods. This is due to its high degree of realism, which includes the detailed characterization of its underlying system dynamics between its components, and the holistic approach it takes to evaluate the performance of its physical counterpart. In the case of the Artemis Base Camp digital twin, this capability is even more essential. Both the manpower and material resources on the lunar base are limited. Uncovering adverse higher-order effects before they manifest themselves into crises that would jeopardize the well-being of the occupants and the success of the mission.

3.3 Astronaut Training

Astronaut training is a critical and integral component of any crewed mission to outer space. Typically, such training takes place in a physical simulator facility on Earth that mirrors the expected conditions in outer space, with a high degree of realism. Simulator facilities such as the Space Station Training Facility, Neutral Buoyancy Lab, NASA Extreme Environment Mission Operations undersea analog missions, and the Martian Habitat Analog Missions have been developed and used by NASA to train astronauts to perform various mission tasks.

However, unforeseen circumstances in outer space may arise frequently, and it is beneficial that such events should be faithfully captured in the training simulators in order to prepare astronauts for as comprehensive a range of scenarios as possible. As mission crews rotate to maintain a sustained presence at the Artemis Base Camp, the training they receive on Earth to be thoroughly familiar with the equipment and operations of the Camp before the new crew's deployment is essential in minimizing disruption and ensuring the continuity of the mission. Furthermore, according to NASA's Plan for Sustained Lunar Exploration and Development, the Lunar Gateway, which orbits around the Moon and serves as a harbinger to the Artemis Base Camp, will also be used to simulate future voyages to Mars. The idea is to have a four-person crew traveling to the Gateway and living aboard for several months, simulating the journey in a spaceship going to and returning from Mars. Training astronauts to adapt to the life on the Gateway also impacts the long-term mission planning for crewed missions to Mars. One element of astronaut training is to assess how astronauts with different personality traits may work with each other in an extreme environment such as the lunar habitat. Arguello et al. (2023) studied the use of Agent-Based Modeling (ABM) to model how the inhabitants' different personalities impact the population survival in a future Martian colony. Its simulation results determined that 22 was the absolute minimal number of inhabitants needed to make a Martian colony viable. In this study, in the absence of an actual Martian habitat environment, the researchers had to rely on data from submarines, Arctic exploration, and war as surrogates of isolated, high-stress environments.

Digital twins have been proposed as a key element of training across many fields, including training for workers in chemical plants (Ottewell 2023), surgery training for residents (Ahmed et al. 2020) and augmented reality training for maintaining high speed rail stations (Pauley 2020). A digital twin model of the Artemis Base Camp, as described in Section 3.1, could also be employed to inform and enrich astronaut training. The base camp model can be developed as an intermediate step between the lunar base and the training facility and simulators on Earth, as shown in Figure 2. Sensors at the Artemis Base Camp can collect data of various types from all the systems and transmit it to the digital twin model. By analyzing these data, the digital twin can generate relevant information that captures the daily routines and anomalies that occur on the lunar surface that the inhabitants of the base camp have to contend with. It then passes this information to the training facility and simulators, which digest the information and integrate it to reinforce existing astronaut training exercises and simulation scenarios with improved realism.

Note that in this use case, the digital twin receives data from the Artemis Base Camp to enhance the realism of astronaut training environment. However, data generated by the digital twin model does not loop back to its physical twin on the lunar surface.

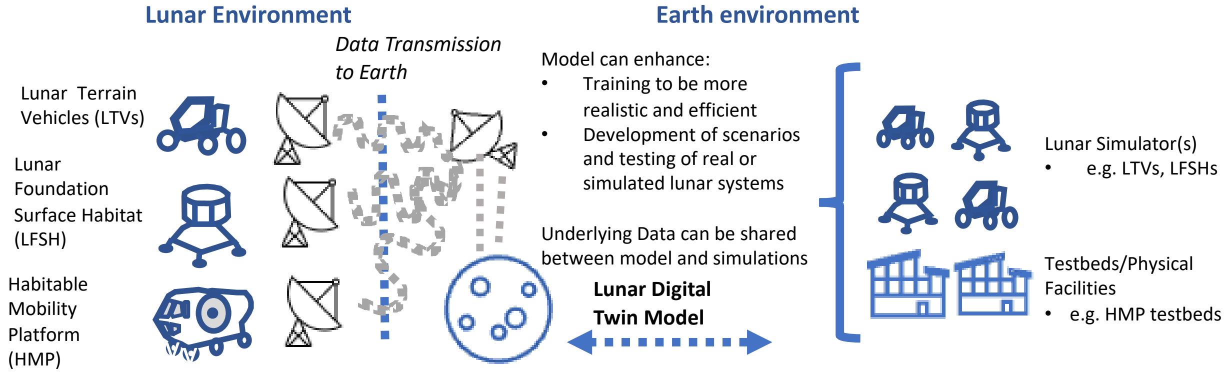

Figure 2: Digital twins for astronaut training.

3.4 Modeling Lunar Community Expansion

The Artemis Base Camp encompasses more than the LTV, Habitable Mobility Platform, and LFSH. Future plans call for expanding it into a community that would support more inhabitants and expand its capacity for longer-term missions. Future expansion of the base camp could also include a hopper that delivers payloads all over the Moon, and a lunar far-side radio telescope (NASA 2020a). Both systems, and their supporting infrastructure, could be operated by the crew from the base camp.

The conceptualization of an expanded lunar community can benefit from leveraging DTs to play out different settlement configurations, from which the most optimal one can be chosen. New installations and systems can be integrated into the existing digital twin model in a modular and evolutionary manner. Supported by the real-life data that went into the existing digital twin model and the ground-truth knowledge of the new addition, this gradual approach retains the ability for the stakeholders to holistically analyze the updated digital twin model and iteratively evaluate the best configuration with each new addition. This application of digital twins would help greatly reduce uncertainties commonly associated with integrating new technologies into an existing and framework, and it would save considerable resources in doing so.

Beyond the U.S. plans, international policies drive the long-term planning for governmental and commercial development of the lunar surface habitats. The human, environmental and business impacts of different international policies can be understood via a digital twin. For example, the digital twin could model options for standardizing building structures and construction, surface transportation, and community services for evolving timeframes. The model could also evaluate different emergency scenarios among global partners to drive international safety standards. The model inputs could be developed via collaboration between international partners. The outputs could reduce the overall individual country costs of lunar habitation and increase safety and efficiency.

4 CHALLENGES OF DIGITAL TWINS FOR SUSTAINED HUMAN HABITAT

Despite its obvious strengths and wide applicability, DTs face several hurdles if they are to be successfully adopted in the Artemis Base Camp development. In this section, we describe several challenges that need be first overcome before digital twins can be effectively applied. Successfully addressing these challenges would not only pave the way for the DT's adoption by the Artemis Base Camp, but it would also positively impact its use in other domains, boosting stakeholder confidence in the results that digital twins produce.

4.1 Digital Twin Model Verification and Validation

Verification and Validation (V&V) ensures a system model not only meets the specification requirements (i.e., verification), but also performs as expected (validation). While V&V for traditional models has established a well-practiced, codified methodology, for digital twin models, it remains a largely ad hoc and discretionary exercise without much confidence that the V&V was properly performed. The literature has recently begun to investigate how robust V&V can be applied to digital twins. Hua et al. (2022) summarized four general strategies of digital twin model validation, including manual/visual inspection, property testing, model-based testing, and machine learning-based validation. In the same paper, the authors also examined challenges of validating digital twin models, and suggested several areas of study (e.g., Uncertainty and Sensitivity Analysis, and transfer learning, and combining expert knowledge and collected data) to enhance the robustness of DT validation. Lugaresi et al. (2019) proposed a signal processing-based real-time validation scheme for digital twins of manufacturing systems.

However, most studies in the published literature have not explored the V&V of a system-of-systems DT, which can be used to characterize a sustained human habitat on the lunar surface. The Artemis Base Camp represents a complex social-technical system of systems, and there is no precedent that can inform its establishment and operation. As such, the digital twin V&V of its individual components, as well as a whole, has not been well studied and understood. This indeed represents a significant risk should a digital twin, given its many advantages, be introduced into the lifecycle of the Artemis Program as a robust analytical and decision-support tool.

4.2 Use of Digital Twins across All Stages of System Lifecycle

There has been much discussion and increasing recognition about leveraging a single digital twin being applied to all stages of its physical counterpart's lifecycle. Hribernik et al. (2006) presented the concept of Product Avatar, a product-centric information management tool. Product Avatar could be seen as a rudimentary digital twin applied to the creation, production, distribution, and end-of-life treatment stages of the product lifecycle. The paper, however, provided a conceptual framework without any implementation to assess its validity. Birk et al. (2022) conducted a survey in the literature on several approaches of automatic generation and updating of digital twins used in the estimation and control of process industrial systems. However, little work has been reported to turn this concept into practice, and few examples of case study exist in the published literature. To the best of our knowledge, there is currently no known best practice where a single digital twin is enabled across several, let alone all, stages of the system lifecycle. The main difficulty is that each lifecycle stage has different objectives, and the digital twin of a stage is configured to assess that particular objective. Once it transitions to the next stage (e.g., from conceptual design to development), the objective changes, and the digital twin needs to consume different data sets to make informed analysis of the new stage.

While it may not be necessary to utilize just one digital twin throughout the lifecycle of the Artemis Base Camp, having the ability to do so would considerably minimize the cost of building new digital twins, shorten the development time, and reduce inconsistency between the different lifecycle stages.

4.3 Communications Network That Supports the Data Transport

At least during the early stages of the Artemis Program, given resource and technical constraints, the DT supporting the design, development, production, crew training, operations, and management of the Artemis Base Camp is likely to be established on Earth. As it is a data-driven modeling paradigm that relies on the continuous input of data from its physical counterpart, it requires a communications network with sufficient bandwidth capacity to transport between Earth and Moon. NASA's proposed LunaNet ("Internet on the Moon") has envisioned a bandwidth baseline of 110Mbps in 2023, ramping up to 950Mbps in 2035 (Schier 2022), to support all lunar-surface activities. In the LunaNet architecture, data exchange between Moon and Earth is handled by the Lunar Reconnaissance Orbiter (LRO) and the Gateway, where operational optical communications aim to provide high bandwidth needs and data aggregation to accomplish efficient spectrum usage. As this networking resource is shared by all facets of the mission, the bandwidth and time allocated to the DT information sharing will be further constrained. NASA is also developing a next generation, greater than 100 Gbps Optical communications relay through the Space Communications and Navigation (SCaN) program (Park et al. 2019). A next generation optical relay node will be the first element in an optical networking constellation, with NASA's nodes aggregating traffic at data rates of up to 10 Gbps from users on the earth's surface up through suborbital, Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Geosynchronous Earth Orbit (GEO), cislunar and beyond. These future communications networks will be fundamental to supporting exchange of information between Moon and the Earth-based DT.

Key metrics in communications such as throughput, latency, and message completion rate all affect the robust functioning of the DT (The propagation delay between Earth and Moon is about 1.3 seconds. Since the duration from the time the digital twin receiving data from the Moon to its sending information to the Artemis Base Camp is likely on the order of minutes or hours, this propagation delay is negligible). To make effective use of the communications network, innovative solutions in the fields such as signal modulation, source coding, error detection and correction, data reduction, and data transport scheduling will need to be developed.

4.4 Fusion of Collected Data and Expert Knowledge

The enormity and complexity of the Artemis Program also represent an unprecedented challenge in space exploration with few precedents to draw on. Experience gained from NASA's other programs (e.g., the International Space Station), can inform Artemis and develop insights into the lifecycle of the lunar human habitat. A DT typically draws input data from four sources: historical data sets, live data from the physical twin, synthetic data, and expert knowledge. Fusing these data sources effectively to drive a robust digital twin ensures the digital twin model is of high fidelity that can produce sensible courses of action and reinforce the physical twin. Investigations into the challenges of space exploration can benefit from such a study. For example, (Arguello et al. 2023) developed an agent-based model of a Mars colony and its inhabitants to study the personality traits and their impact on the population size of the colony, which was linked to measuring the effectiveness of the Martian colonization program. The researchers of this study chose polar exploration crews and submarines as surrogates for extreme environments (Driskell et al. 2018), and such knowledge was then combined with the collected Mars data to build the model.

There is a need to understand how best to fuse collected data and expert knowledge to support enhanced modeling and its efficacy in the resultant model. Niloofar and Lazarova-Molnar (2021) investigated this problem, but a viable solution remains elusive, and such a solution may need to be context-dependent.

5 CONCLUSION

In this paper, we explored a viable application of DTs in the Artemis Program to inform the ideation, design and development, astronaut training, operation, and management of the Artemis Base Camp. By viewing the Artemis Base Camp as a complex, social-technical system of systems, we discussed how DTs could be applied to address several key considerations, such as environmental hazards, extreme access, logistics, transportation planning, autonomous robotics and policy that are critical to the success of the lunar missions. While digital twins hold great potential in being a tool for analysis and decision support, many challenges remain for it to be effectively deployed for establishing a sustained lunar presence. These challenges include V&V of the digital twins, applying digital twins across all stages of the base camp's lifecycle, the transport of data and information between the Moon and Earth, and the fusion of collected data and expert knowledge.

Moving forward, several tasks should be considered to explore the feasibility of employing DTs to support a sustained lunar surface human presence. The first step is to develop a foundational digital twin of the base camp by creating a federation of digital twins representing its various elements; the foundational digital twin shall also include a high-fidelity model of the lunar environment. This could be done in part by leveraging the existing NASA tools and artifacts. Furthermore, studies should be carried out to develop requirements that determine the relevant data sent from Moon to Earth that can be fed into the foundational digital twin. Finally, a well-practiced V&V methodology is also needed to ensure robust DT performance.

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