

COMPREHENSIVE MULTI-ENVIRONMENT OPERATIONAL DESIGN DOMAIN TAXONOMY FOR INTELLIGENT SYSTEMS SAFETY DESIGN

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Abstract

In designing and deploying safety-critical intelligent systems, understanding and defining the operational environment are pivotal for ensuring the system's reliability and robustness. This paper introduces a comprehensive framework for a meticulous Operational Design Domain taxonomy process tailored to Intelligent Systems (IS) design and verification, particularly those integrating machine learning components and dataset development. The process systematically identifies and categorises environmental conditions—from natural lighting and weather to infrastructural and cultural variations—influencing the system's operational efficacy. The taxonomy considers air and land environments (extendable for sea and space in the future). The methodology begins by enumerating environmental aspects that an intelligent system must recognise and adapt to, especially when operating in complex areas. Then, it includes manmade ecosystem features. Each environmental parameter is meticulously defined to cover the range of variability and incorporated into a structured grading system (Grade A to E), which classifies environments from ideal to extremely challenging based on criteria such as lighting, weather conditions, and geographical features.

Keywords

Systems Thinking, Operational Design Domain, Intelligent Systems, Safety Engineering, MBSE.

A. Introduction

The Operational Environment Definition process plays a crucial role in the architecture of trustworthy Intelligent Systems (IS), particularly those utilising machine learning components (Mehlhorn, Richter, & Shardt, 2023). It aids in defining a wide range of environmental conditions under which the system must function reliably (BSI, 2020). These conditions inform the type and variety of data required to train and test intelligent components such as machine learning. Understanding the operational environment facilitates the engineering of comprehensive datasets that capture safety requirements by addressing all critical Operational Domains. This process also guides the creation of robust, trustworthy, intelligent systems that can effectively operate in real-world conditions, thereby enhancing their practical applicability and reliability.

When we reviewed the literature, to the best of our knowledge, we realised that no generic ODD covers a variety of IS. The ODD literature predominately tackles autonomous road vehicles and does not address various IS operational environments (air, space, sea or subsea). This paper is part of a series of papers aiming to develop a trustworthy systems engineering method to assure the trustworthiness of intelligent systems (Al-Shareefy, Butler, & Hoang, 2023) (Al-Shareefy, Butler, & Hoang, 2024). We used an aerial drone system as a case study to validate our method, and part of it was developing a perception system. here, we needed an appropriate ODD for aerial drone development that covers all possible environments in which a drone may operate. The ODD literature did not give us a satisfying answer. Therefore, we realised the usefulness of a comprehensive general ODD that provides baseline features that

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cover a variety of IS applications (space, land, air, and sea). In this work, we will focus on Land and Air applications, and in the future, we will incorporate sea-level, subsea and space.

B. Literature review

The literature suggests a hierarchical taxonomy to help model and understand ODDs (Mehlhorn, Richter, & Shardt, 2023). Standards such as the BSI PAS 1883 (BSI, 2020) and ISO 34503 (International Organisation for Standardisation, 2021) seek to enhance the taxonomy requirements by specifying environmental elements' measurability and definition formats. Other significant contributions include the SAE AVSC lexicon (AVSC, 2020) and ASAM OpenXOntology (ASAM e.V., 2021), which aim to standardise and extend the taxonomy for autonomous vehicle (AV) systems. The proposed ODD taxonomy by NHTSA (NHTSA, 2018) and other related standards are primarily tailored for self-driving cars. The focus is on scenarios and conditions relevant to road vehicles, including roadway types, traffic conditions, and specific environmental conditions that impact vehicular traffic. This specialisation means the taxonomy does not comprehensively address the broader range of autonomous systems. For instance, autonomous drones, underwater vehicles, or robotic systems operating in industrial environments have different operational needs and constraints that are not covered in this taxonomy. The taxonomy lacks detailed consideration of complex landscape shapes and terrain variations. While it mentions roadway geometry and surfaces, it does not extend to more intricate environmental structures that might be encountered by autonomous systems operating off-road or in non-urban settings. There are other domain-specific ODD taxonomies; for example, Ugé (Ugé & Hochgeschurz, 2021) specifies a taxonomy for above-sea-level marine applications. Another ODD related to the mining industry (Castellanos-Ardila & al., 2022) extends the existing taxonomies with mining operational domain aspects. In summary, the taxonomy in Exhibit 1 integrates all taxonomies reviewed in this literature.

Exhibit 1 presents a partial view of the comprehensive Operational Design Domain (ODD) taxonomy tailored for autonomous motor vehicles. The full table contains 5 levels and can be found in (Al-Shareefy H., 2024). The full version of this taxonomy is organised into 5 levels, each detailing the essential attributes and categories that define the operational environment of autonomous road vehicles. The hierarchical structure ensures a thorough understanding and classification of all relevant factors influencing the performance and safety of autonomous vehicles.

C. General ODD for IS safety design derivation method

We devised the following method to produce a general Operational Design Domain (ODD) for Intelligent Systems (IS), involving a series of systematic actions to ensure comprehensive coverage and applicability across various domains such as sea, air, space, and land. This process aims to create a robust ODD framework that can be applied universally to enhance the safety and functionality of IS. The steps taken in this method include:

1. Gathering Existing ODD Schemas

The first step involved collecting ODD schemas from established standards and peer-reviewed research papers. This step was crucial to identifying and consolidating common elements and patterns in existing ODD frameworks. We established a solid foundation for deriving a generalised ODD by creating a comprehensive database of current ODD standards. This foundational database ensures that our ODD framework is built on widely accepted principles and methodologies.

2. Inferring Common Abstract Patterns

Next, we analysed the collected ODD definitions to infer common abstract patterns. This analysis aimed to identify recurring themes and elements that are universally applicable across different types of IS. By distilling these common patterns, we were able to highlight the core components of an ODD that are essential for any IS, regardless of its operational domain. This set of abstract patterns is the backbone of our generalised ODD, ensuring it is comprehensive and adaptable.

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Exhibit 1. State-of-the-art Integrated ODD taxonomy for autonomous motor vehicle

Level 1: Class	Level 2 Attribute
Physical Infrastructure	Roadway Types
	Roadway Surfaces
	Road Surface Conditions
	Roadway edges
	Roadway Geometry
	Lane specification
Operational constraints	Speed limit
	Traffic conditions
Objects	Traffic control devices
	Signage
	Roadway users
	Non-roadway user obstacles/objects
Connectivity	Vehicles
	Traffic density info
	Crowdsourced data
	V2I
	Remote fleet management system
	Communication obstructions
	Infrastructure sensors and communication
Weather-related conditions	Probability forecast
	Wind
	Precipitation types
	Sun angle
	Haze
	Sky condition
	Temperature
	Weather-induced roadway conditions
	Particulate matter
	Illumination (luminous flux)
Zones	Geo-fencing
	Traffic management zones
	School/construction zones
	Regions/states
	Interference zones
	Dynamic zones
Additional categories	Non-static roadside objects
	Additional requirements

3. Utilising Engineering Judgment

In addition to analysing existing schemas, we relied on our experience and engineering judgment to consider potential aspects of the ODD that existing definitions may not cover. This step involved incorporating practical insights and experiences to enhance the ODD's relevance and applicability. By including expert-driven considerations, we enriched the ODD framework, making it more robust and capable of addressing real-world challenges that may arise during the operation of IS. This approach ensures that our ODD is theoretically sound and practically viable.

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D. Patterns Observed in Combined Autonomous Road Vehicles ODDs

Several patterns were identified after reviewing the results of combining available ODDs for autonomous road vehicles. These patterns highlight the key elements typically included in ODD frameworks for road-based unmanned vehicles and provide a basis for generalising the ODD for other IS types:

1. Natural Environmental Factors

These factors encompass various elements of the natural environment that can significantly influence the operation of Intelligent Systems (IS). These elements can create challenges or operational constraints for IS, affecting their functionality, efficiency, and safety. Weather conditions such as rain, snow, fog, and temperature variations are primary natural environmental factors. For instance, heavy rain can reduce visibility and sensor accuracy; snow can obstruct roadways and create slippery surfaces; fog can limit visual and sensor range; and extreme temperatures can impact the performance of batteries and electronic components in IS.

2. Dynamic (Impermanent) Physical Natural Object Factors

These factors include natural objects or entities that are transient, moving, or changing over time. Their impermanent nature means they can appear, disappear, or move unpredictably, thus posing potential hazards or requiring adaptive responses from IS. Pedestrians, animals, and flooded areas are key examples. Pedestrians can suddenly step onto the road, animals might cross paths unexpectedly, and flooded areas can emerge after heavy rains, necessitating real-time detection and response by IS to avoid accidents or damage.

3. Dynamic (Permanent) Engineered Physical Object Factors

This category covers human-made objects that are inherently in motion or change their state over time. These factors are dynamic but are part of a predictable system, such as traffic flows or operational machinery. Road traffic flow, moving vehicles, and construction equipment are typical examples. Traffic flow dynamics include varying speeds and densities, moving vehicles introduce variable obstacles, and construction equipment can change positions or create temporary barriers, all of which IS must navigate efficiently.

4. Static (Permanent) Natural Physical Object Factors

This category includes stationary natural objects that do not change over time. These objects are part of the natural landscape that IS must detect and navigate around consistently. Trees, mountains, and geological formations exemplify static natural objects. Trees can line roadsides; mountains may define terrain boundaries, and geological formations can create fixed obstacles, all requiring IS to map and avoid them accurately during operations.

5. Static (Permanent) Engineered Physical Object Factors

These are stationary, human-made structures that are permanently fixed in place. They form part of the consistent, unchanging landscape that IS must recognise and interact with appropriately. Such factors include road lanes, bridges, buildings, and traffic signals. These objects provide structure and guidance for IS operations, such as lane markings for navigation, bridges to avoid obstacles, buildings for GPS references, and traffic signals to control movement.

6. Engineered Zones

Engineered zones are specific areas designed and designated for particular purposes that can impact IS operations. These zones often have specific rules, constraints, and environmental settings that IS must adhere to. School zones, construction zones, and geo-fenced areas are typical examples. School zones require reduced speeds and heightened awareness, construction zones may include temporary detours and machinery, and geo-fenced areas define operational boundaries for autonomous systems.

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7. Communication Network (Informational Exchange)

This factor pertains to the systems and networks used for exchanging critical information necessary for the functioning of IS. Effective communication networks ensure that IS can receive, process, and respond to real-time data for safe and efficient operations. V2V (Vehicle-to-Vehicle), V2I (Vehicle-to-Infrastructure), GPS, and remote fleet management systems are crucial components. V2V communication allows vehicles to share information about their speed and position, V2I enables interaction with traffic signals and road infrastructure, GPS provides location data, and remote fleet management systems offer oversight and control for multiple IS units.

E. Limitations of Current ODD Frameworks for Road Unmanned Vehicles

Refer to the following repository for the combined existing ODD taxonomy (Al-Shareefy H. , 2024). The identified patterns and elements in existing ODD frameworks are specifically tailored to address the operational needs of autonomous road vehicles. While these frameworks provide a foundational understanding of the operational design domain for road-based unmanned vehicles, they exhibit several limitations when applied to other types of Intelligent Systems (IS) operating in different domains such as sea, air, and space.

1. Domain-Specific Constraints

One major limitation is the domain-specific nature of the existing ODD frameworks. These frameworks focus primarily on scenarios and conditions relevant to road vehicles, including roadway types, traffic conditions, and specific environmental conditions that impact vehicular traffic. This specialisation means the taxonomy does not comprehensively address the broader range of autonomous systems. For instance, autonomous drones, underwater vehicles, or robotic systems operating in industrial environments have different operational needs and constraints not covered in this taxonomy. For example, underwater vehicles must navigate complex three-dimensional spaces and deal with factors such as water pressure, salinity, and marine life, which are not considerations for road vehicles.

2. Lack of Consideration for Non-Road Environments

Another significant limitation is the lack of detailed consideration for complex landscape shapes and terrain variations that might be encountered by autonomous systems operating off-road or in non-urban settings. While the current ODD frameworks mention roadway geometry and surfaces, they do not extend to more intricate environmental structures such as rugged terrains, dense forests, or mountainous regions. This omission can be problematic for IS designed for off-road or cross-terrain navigation, where operating conditions differ vastly from typical urban or suburban roadways.

3. Inadequate Addressing of factors affecting aerial applications

Due to the domain-specific constraint, The existing ODD frameworks also inadequately address the unique conditions and challenges aerial and autonomous systems face. For example, the frameworks do not consider airspace classifications, altitude-based weather conditions, or navigational hazards such as bird strikes for aerial vehicles. Similarly, for marine systems, there is a lack of focus on underwater topography, water currents, and buoyancy challenges. These omissions mean that the current ODD frameworks are not equipped to handle the specific operational domains of aerial and marine IS, which require tailored considerations for safe and efficient operation.

F. General ODD process

To address the limitations mentioned above, a general ODD definition process may be useful to standardise the process of defining operational domain taxonomies. When considering IS, we focus on its “*intelligence*” as an abstract emergent quality hosted and supported by some cyber-physical platform. Therefore, the General ODD is a definition of an operational environment that affects and is affected by the “*intelligence*” of some IS. In general, An Operational Design Domain (ODD) for various types of

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Intelligent Systems (IS), those operating in sea, air, space, or land domains, should encapsulate a range of abstract features to ensure comprehensive coverage. These features are categorised into two main taxonomies: Natural and Man-made related features. Here is a general ODD characterisation process that defines the minimum information needed for a comprehensive ODD:

Step 1: Define natural surrounding ODD taxonomy:

- 1. Dynamic or cyclic changing natural classes:** Classes of factors that include elements that move or change position. Also, it includes cyclic state-based phenomena.
 - Example: birds, fish, wind currents, seasonal changes (spring, summer, autumn, winter), tidal changes.
- 2. Static natural classes:** Classes of factors that include relatively stationary natural elements.
 - Example: trees, rocks, coral reefs. In the space domain, this may include the sun, moon or any relatively stationary celestial objects (including far stars in the background).
- 3. Natural surrounding noise and interference classes:** Natural ambient noise and interference refer to the background sounds and signals originating from natural sources that can impact the functionality of an IS. These noises and interferences are typically omnipresent and can vary significantly depending on the operational domain.
 - Example: an underwater drone encountering communication difficulties due to the echolocation clicks of dolphins or the noise from underwater volcanic activity.

Step 2: Define manmade surroundings taxonomy:

- 1. Informational environment classes:** Classes of factors that include the set of informational signals and data streams generated by human-made systems that assist or influence the operations of an IS.
 - Example: a GPS navigation system providing turn-by-turn directions to a vehicle.
- 2. Dynamic or changing engineered classes:** Classes of factors that are human-made elements that move or change position.
 - Example: traffic signals (changing from red to green), cars, trains, aircraft, cultural events.
- 3. Static or static engineered classes:** Classes of factors are human-made elements that remain stationary.
 - Example: bridges, buildings, roads, dams.
- 4. Manmade surrounding noise and interference classes:** Classes of factors that include man-made engineered noise and interference encompass unwanted signals or disruptions generated by human-made systems that can impact the functioning of an IS.
 - Example: These can include electromagnetic interference (EMI), radio frequency interference (RFI), acoustic noise, and other disturbances.

These categories ensure that relevant aspects of an IS's environment are considered, allowing for safer and more effective operation within its designated domain.

G. Comprehensive ODD Definition that combines Land and Air-based IS applications

For full taxonomy, refer to (Al-Shareefy H. , 2024). The general ODD process outlined above was systematically applied to create a comprehensive Operational Design Domain (ODD) framework encompassing land and air-based Intelligent Systems (IS). This comprehensive ODD framework ensures that all relevant aspects of the operational environment are considered, allowing for safer and more effective operations within their designated domains. The following elaboration details how each step of the general ODD process was applied to combine land and air-based IS applications.

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Step 1: Define natural surrounding ODD taxonomy:

1. Dynamic or cyclic changing natural classes

The process involved identifying natural factors that are constantly moving or periodically changing to account for dynamic or cyclic changing natural classes. These factors are crucial for understanding the environmental variability that IS must adapt to.

- **Weather Conditions Variety:** This includes a comprehensive range of weather conditions such as temperature, precipitation, wind, humidity, pressure, and visibility. For instance, temperature variations can significantly impact the performance and efficiency of IS, particularly those with sensitive electronic components or battery dependencies.
- **Time of the Year Seasons-specific Changes:** Seasonal changes, including spring, summer, autumn, and winter, bring distinct environmental conditions that affect IS operations. For example, winter may introduce snow and ice, obstructing pathways and reducing sensor accuracy, while summer may present heat waves affecting cooling systems.
- **Illumination Variety Definition:** This includes variations in natural light conditions such as sunrise, sunset, twilight, and night. Additionally, it considers the positioning of celestial bodies like the moon, which affects visibility and navigation for both land and air-based IS, particularly during nighttime operations.

2. Static, unexpected, or non-cyclic changing natural classes

These classes include natural elements that remain relatively stationary or do not follow a predictable cycle but still influence IS operations.

- **Landscape Types Variety:** The variety of landscapes, such as urban, suburban, rural, mountainous, forest, desert, coastal, water, industrial, and arctic landscapes, is considered. Each landscape type presents unique challenges and considerations for IS, such as the need for urban navigation algorithms or rugged terrain handling capabilities in mountainous regions.
- **Geographical Region-specific Natural Phenomena:** This includes phenomena unique to specific regions, such as atmospheric phenomena (e.g., northern lights, monsoons), hydrological phenomena (e.g., floods, tsunamis), geological phenomena (e.g., earthquakes, volcanic eruptions), and biological phenomena (e.g., animal migrations).
- **Perceived Visible Horizon Attitude:** This involves the perception of the horizon as captured by IS sensors, which includes image rotational movements like frame roll and pitch. Understanding how the horizon is perceived helps calibrate sensors and ensure accurate navigation and stability.

3. Natural surrounding noise and interference classes

Natural ambient noise and interference can significantly impact the functionality of IS. These factors are typically omnipresent and vary depending on the operational domain.

- **Natural Auditory Noise:** This includes noise from wind, animal sounds, vegetation movement, and thunderstorms. Such auditory noise can interfere with acoustic sensors and communication systems, necessitating robust filtering and noise-cancellation techniques.
- **Natural Non-audio Interference** includes electromagnetic interference (EMI) from natural sources such as solar flares and terrain-induced interference. Such interference can disrupt electronic systems and communication links, requiring IS to be equipped with shielding and error-correction capabilities.

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Step 2: Define Manmade Surroundings Taxonomy

1. Informational Environment Classes

This step involves identifying the set of informational signals and data streams generated by human-made systems that assist or influence IS operations.

- **Road Transport Connectivity:** This includes Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication systems that provide real-time traffic information, navigation guidance, and safety alerts.
- **Railways Transport Connectivity:** This includes communication systems between trains (Train-to-Train) and between trains and wayside infrastructure (Train-to-Wayside) for coordinated operations and safety management.
- **Air Travel Connectivity:** This includes communication systems for airborne vehicles, such as Airborne Vehicle-to-Infrastructure (V2I) and Airborne Vehicle-to-Airborne Vehicle (AV2AV) communications, essential for air traffic management and collision avoidance.

2. Dynamic or Changing Engineered Classes

This step focuses on human-made elements that move or change position, affecting IS operations.

- **Road, Train, and Air Traffic Conditions:** Dynamic traffic conditions require IS to adapt to varying speeds, densities, and flow patterns in real time.
- **Dynamic and Impermanent Road, Train, and Aerospace Objects of Interest:** This includes temporary obstacles, construction zones, and other transient objects that IS must detect and navigate around.
- **Socio-Political Factors:** Events like cultural festivals, political gatherings, and public demonstrations can create dynamic changes in the operational environment, requiring IS to adjust routes and operational plans.

3. Static or Static Engineered Classes

This step includes human-made elements that remain stationary and form the consistent landscape within which IS operates.

- **Road, Train, and Aerospace Physical Infrastructure:** Permanent structures like bridges, buildings, roads, dams, rail tracks, and airports provide a stable framework for IS navigation and operations.
- **Static and Permanent Road, Train, and Aerospace Objects of Interest:** This includes road signs, signal lights, and fixed landmarks essential for navigation and operational reference.

4. Manmade Surrounding Noise and Interference Classes

This step addresses unwanted signals or disruptions generated by human-made systems that impact IS functionality.

- **Land-based Noise and Interference Factors:** This includes electromagnetic interference (EMI), radio frequency interference (RFI), and acoustic noise from urban environments, industrial zones, and transport systems.
- **Air-based Noise and Interference Factors:** This includes interference from radar systems, communication signals, and other airborne sources that can disrupt the operations of UAVs and other airborne IS.

We have created a comprehensive framework that covers relevant aspects of land—and air-based IS operations by applying the general ODD process. This framework ensures that the unique requirements and

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challenges of these domains are addressed, enhancing the effectiveness of ODD for Intelligent Systems design in such domains.

H. Reflection

In this study, we have developed and articulated a comprehensive Operational Design Domain (ODD) framework that is both robust and versatile. This general ODD process is designed to systematically address the limitations of existing ODD frameworks, which are primarily tailored for autonomous road vehicles. Our methodology involved gathering and analysing existing ODD schemas, inferring common abstract patterns, and incorporating engineering judgment to enrich the ODD framework. This approach ensures that the framework is theoretically sound and practically viable.

The significance of our work lies in its ability to generalise the ODD definition process across various domains, including sea, air, space, and land. By focusing on the "intelligence" of the Intelligent Systems (IS) as an emergent quality hosted by a cyber-physical platform, our framework captures the essential attributes and categories that define the operational environment affecting and affected by this intelligence. This holistic approach ensures comprehensive coverage of both natural and manmade factors, which are critical for the safe and effective operation of IS.

The approach helped us consider factors that may not have been considered by existing ODD frameworks. Traditional ODD frameworks for autonomous road vehicles often overlook the complexity and variability of other environments. By systematically defining dynamic, static, and noise-related factors in both natural and manmade contexts, we ensure that a wider range of potential challenges and operational constraints are addressed. This comprehensive consideration is crucial for designing safety into intelligent systems, as it allows for anticipating and mitigating a broader array of risks.

Applying our general ODD process to land and air-based IS has demonstrated its effectiveness. By defining a detailed taxonomy for natural and manmade surroundings, we have created a framework that can address the unique operational needs of these domains. For land-based IS, such as autonomous vehicles, we considered factors like dynamic traffic conditions, road infrastructure, and natural environmental challenges like weather and terrain variations. We included factors such as airspace classifications, altitude-based weather conditions, and navigational hazards for air-based IS, including UAVs.

I. Future Work

The extendibility of our Operational Design Domain (ODD) framework represents a significant opportunity for future research and application. The same methodology we applied to define ODDs for land and air-based Intelligent Systems (IS) can be adapted to other operational environments, including sea, space, and extraterrestrial domains such as Mars or the Moon. This flexibility is achieved by categorising the ODD into natural and manmade factors, which can be tailored to each environment's specific conditions and challenges.

Sea Domain:

For IS operating in the sea domain, such as autonomous underwater vehicles (AUVs) and autonomous ships, future work will involve defining ODDs that address the unique challenges of this environment. Factors such as underwater currents, water pressure, salinity levels, and marine life must be considered. These elements influence navigation, communication, and operational safety. Future research must explore how these factors can be effectively integrated into the ODD framework to ensure sea-based IS's reliable and safe operation.

Space Domain:

In the space domain, IS such as satellites, space probes, and rovers must operate under conditions vastly different from those on Earth. Considerations for space-based ODDs will include microgravity, radiation exposure, and the vacuum environment. Additionally, the ODD must account for the orbital mechanics and potential debris present in space. Developing a comprehensive ODD for space IS will require extensive

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research into how these factors impact the functionality and safety of the systems, as well as the development of new methodologies to mitigate associated risks.

Extraterrestrial Environments:

Exploring the ODD for IS operating on extraterrestrial bodies such as Mars or the Moon presents unique challenges and opportunities. Factors such as reduced gravity, extreme temperatures, regolith terrain, and radiation levels must be accounted for. The operational domain for these environments also includes the potential for dust storms on Mars and lunar dust on the Moon, which can affect sensors and mechanical components. Future work will involve detailed studies of these conditions and the development of adaptive technologies to ensure the IS can operate effectively in these harsh environments.

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