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ECLSS 環境における製品・サービスのシステムデザインのための要求分析

Requirements Analysis for Product and Service System Design in ECLSS Environments

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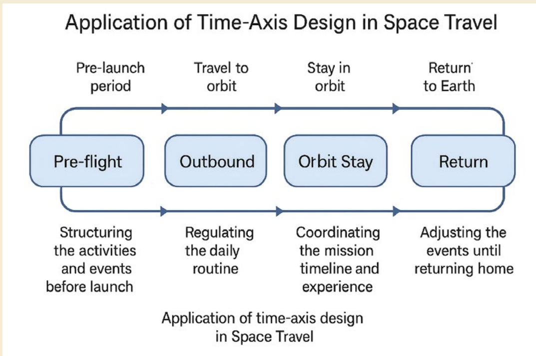
Abstract: Environmental Control and Life Support Systems (ECLSS) have been developed mainly to ensure astronaut survival in closed and harsh space environments. With the projected expansion of civilian space travel in the 2030s and 2040s, new requirements emerge for comfort, well-being, and diverse experiences beyond survival. This study applies requirements analysis to product and service system design in ECLSS environments, introducing the concept of "Comfortable ECLSS." The approach combines stakeholder analysis,



scenario-based modeling, and context-oriented design, focusing on physical, temporal, motivational, and economic conditions. The analysis identifies four requirement categories: (1) physiological and cognitive comfort, (2) experiential and motivational needs, (3) temporal dynamics of user experience, and (4) contextual and economic constraints. Applying timeaxis design shows how expectations, adaptation, and post-experience memory can be systematically integrated into system requirements. The Comfortable ECLSS framework extends conventional life-support design by embedding human-centered perspectives. It provides a foundation for developing inclusive and sustainable space habitats that support both survival and quality of life for civilians in orbit.

Keywords: ECLSS, Human-Centered Design, Space Habitats, Service Engineering, System Design, Comfortability

1. Introduction

Environmental Control and Life Support Systems (ECLSS) have been developed with the primary purpose of ensuring astronaut survival under closed and harsh conditions in space. Oxygen generation, carbon dioxide removal, water recovery, and atmospheric circulation were optimized for reliability, forming the backbone of human spaceflight. However, the Basic Plan on Space Policy approved by the Cabinet of Japan on June 13, 2023, defines the direction of national space policy for the next decade with a 20-year outlook. This plan anticipates the growth of new social and economic activities in space, including the participation of private sector actors. Traditionally, space has been viewed as the domain of astronauts and highly trained professionals carrying out well-defined missions. In contrast, projections now suggest that by the 2040s, approximately 10,000 or more civilians will travel annually to LEO for short stays[1)2)]. This expansion indicates that space stations and orbital platforms will no longer be limited to professional astronauts but will be increasingly accessible to private citizens. Consequently, industries outside of the traditional aerospace sector are accelerating R&D to respond to this new demand.

The environmental conditions of space habitats—including gravity, temperature, humidity, and air/water circulation—differ significantly from those on Earth. Research on Environmental Control and ECLSS[3)] and Closed Ecology Life Support Systems (CELSS)[4)] has enabled astronauts to operate for long durations in orbit. These technological developments have made it possible to sustain human life in space; however, they have primarily been designed to meet minimum survival requirements rather than to enhance overall quality of life. In space, where physical environments and behavioral constraints are drastically different from those on Earth, human perception, cognition, and well-being are expected to be strongly affected. To ensure the success of civilian space travel, it is no longer sufficient to design systems for survival alone. We propose that achieving comfort, well-being, and a level of quality of life (QOL) comparable to that experienced on Earth will be essential for sustaining long-term human presence in space. This study introduces the concept of the "Inclusive ECLSS for Comfortability"[5)], which extends traditional life-support systems to incorporate human-centered requirements. The purpose of this paper is to propose a framework for requirements analysis for the system design of products and services in ECLSS environments.

2. Requirements Analysis for Product and Service System Design in ECLSS Environments

In this study, the product and service system design in ECLSS environments is defined as the integration of terrestrial, non-space technologies and design expertise with the human-centered approach of "Inclusive ECLSS for Comfortability[5)]", which incorporates the unique characteristics of ECLSS environments as well as the cognition, perception, and experiences of the people operating within them. Through this integration, we aim to design products and services that support human comfort in space life.

The Inclusive ECLSS for Comfortability aims to expand beyond minimum environmental control functions and integrate human-centered perspectives. Four major categories of requirements are identified[5)]:

1. *Physiological and cognitive comfort* – management of sensory adaptation and stress reduction.
2. *Experiential and motivational needs* – supporting activities that enable travelers to achieve their diverse purposes during stays in space.
3. *Temporal dynamics of experience* – addressing each phase of the user journey through timeaxis design.
4. *Contextual and economic constraints* – embedding physical, operational, and economic feasibility into system design.

To implement this framework, a multi-layered methodology is applied in requirements analysis for system design.

First, stakeholder analysis is conducted to capture the perspectives of diverse actors, including civilian travelers, infrastructure providers, product suppliers for habitation, service operators, and regulatory authorities. This analysis clarifies not only technical requirements but also the expectations and concerns of multiple stakeholders involved in space habitation.

Second, scenario-based modeling is employed to examine representative cases of space stays, such as one-week tourism in low Earth orbit, one-month research residencies, and long-term habitation. Each scenario highlights distinct requirements related to environmental conditions, psychological adaptation, and service provision, thereby contributing to the extraction of comprehensive design criteria. At this stage, it is essential to account for travelers' purposes as well as individual differences in cognition, perception, and physiology. Timeaxis design[6)7)] is a methodology that visualizes how the value of user experience evolves over time and integrates this temporal progression into design. By considering the temporal transitions of experiential value, it enables consistent design across the stages of pre-use, during-use, and post-use. In practice, this involves tracking changes in users' emotions and cognition over time and applying these insights to system design and operation. Typical trajectories may be expressed as: "pre-stay expectations → in-stay satisfaction → post-stay memory and re-evaluation." This approach is highly compatible with service blueprints and customer journey maps, providing a perspective that frames services not merely as isolated "moments" but as continuous "narratives."

Third, a context-oriented design approach is introduced to classify requirements along four dimensions: physical, temporal, motivational, and economic. This allows systematic mapping of how environmental parameters, temporal dynamics, user objectives, and resource constraints interact to shape the lived experience of space travelers.

Moreover, this approach emphasizes cross-disciplinary integration. Physiology and medicine contribute to health and comfort assurance; sports science and cognitive science enhance QOL and comfort; ergonomics and crossmodal design support sensory and cognitive adaptation; service engineering and behavioral economics assist decision-making and resource optimization; and AI with data analytics enables personalized comfort strategies and adaptive system responses. By integrating these perspectives, the Inclusive ECLSS for Comfortability framework extends beyond conventional engineering, encompassing socio-technical as well as experiential dimensions of human space life.

3. Conclusion

This study proposed the concept of the Inclusive ECLSS for Comfortability, extending life-support systems from survival-centered to human-centered design. By integrating stakeholder analysis, scenario-based modeling, timeaxis design, and context-oriented classification, the framework identifies requirements across physiological, experiential, temporal, and contextual-economic dimensions. Embedding human-centered perspectives enables the design of sustainable and inclusive space habitats that support not only survival but also comfort and quality of life for diverse civilian travelers. As future work, the concrete development of methodologies for requirements analysis and system design can be identified as an important challenge.

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