HaHa: Post-Earth Habitat-Hardware Co-Design for Computing in Space

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"Earth is the cradle of Mankind, but one cannot stay in the cradle forever." -Konstantin Tsiolkovsky, Pioneer of Astronautics

1 INTRODUCTION

Long-term human settlements in space have long been a dream of humanity. Whether driven by ambitious space endeavors[5, 11], degrading Earth's environment[10], or the intrinsic human desire, long-term living in space appears to be an inevitable future.

Studies on space habitation suggest that self-sustaining space habitats may be our future homes. These massive structures are designed to meet our essential needs for air, water, food, shelter, and even recreation[2, 3]. However, the role of ICT in these habitats has been overlooked. Therefore, we argue that it is essential to develop a model of computation that addresses our *computing needs* within the constraints of habitat environment. However, habitats must be self-sustainable, which means they have a stringent power budget and operation conditions meticulously accounted for by individual inhabitants. As a result, integrating computation to fulfill the inhabitants' needs is not trivial.

To that end, in this work, we take the first step of thinking about *the support of personal computation in the highly constrained space habitats.* We mainly address three questions: i) What computation model and system is suitable? ii) How can it be adopted at a low operation and integration cost in the habitat? and iii) How can the habitants utilize it?

To answer these questions, we first identify key constraints for computational systems in these habitats (Section 2). Next, considering these constraints and the needs of the inhabitants, we propose 'HaHa,' our solution to this problem (Section 3).

2 SPACE HABITATS

We start with a background of space habitats and their constraints.

Post-Earth long-term Human Habitats in Space

Long-term human habitats in space can either be planetary space colonies on bodies like Mars or the Moon[1], or orbital settlements in free space[2, 3]. Key challenges for long-term stays include health issues (gravity, radiation, agriculture) and economic factors.

We focus on orbital settlements because: 1) Orbital settlements can provide Earth-like gravity, essential for healthy human development, unlike the lower gravity on Mars and the Moon. 2) Unlike the limited sunlight available on planetary surfaces, they offer continuous and reliable solar energy. 3) Space habitats can achieve self-sustainability in energy, agriculture, and living conditions, reducing reliance on planetary resources. These advantages highlight the scalability of orbital settlements. Studies on space habitats focus on self-sufficiency by addressing food and oxygen needs through agriculture, ensuring healthy living conditions with artificial gravity, radiation protection, and designated living and recreational spaces. Energy self-sufficiency is achieved by harnessing solar power, as habitats are designed for constant sunlight exposure, and through the motion of inhabitants within the habitat.

Computing in Space Habitats

Robust computing systems are essential for meeting life support demands, including environmental monitoring and communication. As space habitats focus on self-sufficiency, research has mainly focused on environmental factors and human adaptation, often overlooking the need for efficient, scalable computing frameworks tailored for the unique challenges of space habitation, such as power limitations, hardware reliability, and network constraints.

CH#1: Strict Power Constraints: Energy in these habitats relies mainly on solar panels. In the habitat model shown in Figure 1(b), these panels cover the outer surface. A portion of the harvested power is used for habitat maintenance and life support, leaving only a small fraction for computing. For habitat design under consideration[3], the maximum power budget for computation is 10KW, while the best-case power consumption using current Earth models is 234KW. Therefore, power is a critical constraint for computing hardware, requiring highly efficient systems.

CH#2: Changed Operating Environment: The space environment introduces several operation challenges for computers.

- **Radiation Shielding**: Space habitats face high levels of cosmic and solar radiation, damaging computing hardware and leading to system failures or data corruption. This implies added costs for radiation hardening of hardware.
- **Temperature**: Placement of computational hardware in habitats significantly impacts power constraints. If located in livable areas, it increases maintenance power costs. Conversely, placing it outside these areas poses challenges due to extreme temperatures ($2 \sim 3K$) and radiation.
- **Sourcing the Hardware**: Sourcing materials from Earth incurs a one-time significant cost related to the number of computational hardware units. Post-life processing also add pollution and waste management challenges, challenging the maintenance of multiple hardware units per inhabitant.

CH#3: Dynamic Network Behavior: We suggest utilizing optical interplanetary internet (IPN) for communication networks instead of habitat-specific LANs. This approach emphasizes interoperability between habitats, scalability, and inclusivity. IPN consists of satellites that communicate with one another, but it has challenges such as signal delays, limited bandwidth, and potential disruptions, which can complicate data transmission and real-time operations.

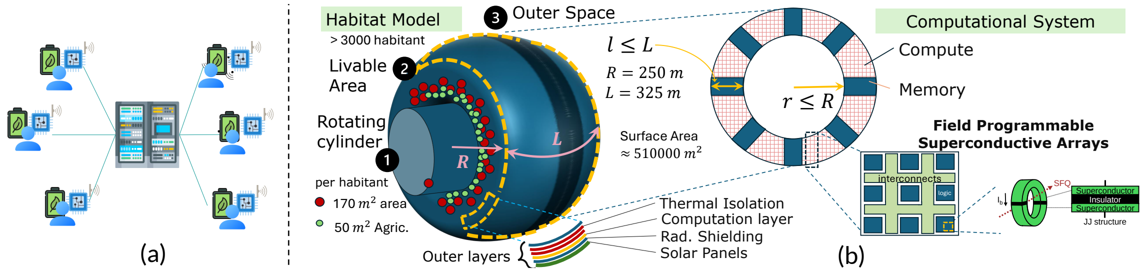

Figure 1: System architecture and placement. (a) Centralized computation model with self-powered user nodes and a reconfigurable FPSA-based computer. (b) Integration between the shielding and temperature isolation layers outside the livable area.

Given these challneges, we introduce a computing model 'HaHa' power-efficient, high-performing, and adaptable computing hardware for space habitats addressing three key research questions:

(1) What is a suitable model of computation to adopt?
(2) How to integrate this model into the habitat?
(3) How to efficiently utilize this model hardware resources?

Next, we discuss the details of the hardware system architecture (Section 3.1), its placement within the habitat (Section 3.2) and scheduling for efficient utilization of this system (section 3.3).

3 HAHA: HABITAT-HARDWARE CO-DESIGN

While convenient, we argue that the current distributed computing model is not the best option given our unique challenges. Current systems consume too much power per calculation to fit within our strict power budgets (CH#1). Furthermore, the current distributed computing model may not be the best choice due to its overheads and limited adaptability for efficient long-term operation (CH#2). Therefore, we propose adopting a centralized model.

3.1 The Computing Hardware

HaHa proposes a runtime reconfigurable central processor with superconductive logic elements - called *Field Programmable Superconductive Arrays* - FPSA. The FPSA allows the same hardware to be used efficiently for several applications, making it adaptable while maintaining performance efficiency even when applications change. Furthermore, the superconductive technology allows ultra-low power operation with more than 1000 times lower energy per switching compared to present-day systems. As the temperatures in habitats (except the livable areas) are reported close to $\sim 3K$, the cooling overhead of FPSAs, when placed correctly, vanishes. This motivates the FPSA-based centralized processor.

The nodes to communicate with FPSAs are ultra-low power devices with basic processing functions. They follow intermittent execution[6], solely running on harvested energy[4, 8].

3.2 Placement of Computing Hardware

Placing the hardware system in habitats affects power consumption, radiation shielding costs, and inhabitants' accessibility. To efficiently minimize shielding and cooling costs while keeping the FPSAs accessible, we propose placing them near livable areas of the habitat but only within the radiation shielding layers, as shown in Figure 1(b). The compute and memory elements are placed in the inner layer of the elongated cylindrical habitats, creating a 'computation layer' between the outer shielding layers. This can accommodate the personal computing needs of 30000 inhabitants. The 10 kW power budget can support a maximum of 54 billion logic cells in an area of 10000 mm² when implemented similar to [9].

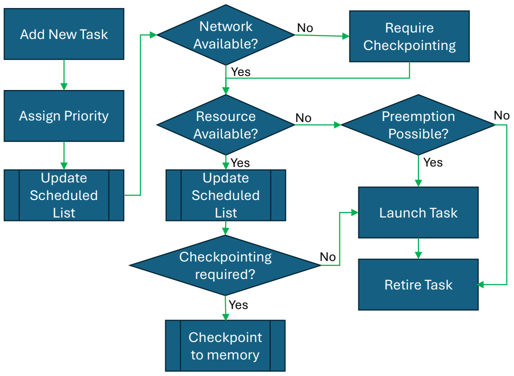

Figure 2: HaHa scheduling algorithm. It leverages the habaitat-hardware integration and use accessible checkpoints as fallback to free resources.

3.3 Ensuring Efficient Computing in Habitat

HaHa first proposes allocating computing resources by regions per inhabitant to utilize resources efficiently. In each of these regions, we propose a preemption-based scheduling with checkpointing for users tasks. Scheduling is required for FPSAs to manage allocations of resources and dynamic network behavior (CH#3). Figure 2 shows the proposed scheduling algorithm. Checkpointing of almost-finished tasks allows context switching by freeing up the allocated resources, while, in case of network failure, it reduces task wait times. Scheduling leverages placement of computation layers to allow users to get their checkpointed results as a fallback in the case of prolonged network unavailability. This can be done by linking the computation layer to the inner livable area for data transfer[7].

4 CONCLUSION

Space habitats are distant but likely in the future. Access to ICT is now a basic human need, and the space computing model remains largely unexplored. In this article, we identify and address the significant challenges of computing in space habitats with 'HaHa'. As the WACI initiative of ASPLOS provides a platform for discussing crucial ideas, we attempt to ignite discussions about computing for human long-term stays in space like tourism and habitation, etc.

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