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Strategies & Architectures as the Framework for Future Building Blocks in Space Exploration and Development (1)

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ARCHITECTING THE FUTURE OF SPACE SYSTEMS: MODULARITY EVOLUTION IN SATELLITE DESIGN

Abstract

The satellite manufacturing industry is experiencing unprecedented disruption as technological innovations and evolving customer demands reshape traditional technical architectures and business models. More than ever, satellite manufacturers operate in a dynamic environment, where lowering engineering costs and shortening manufacturing cycles is crucial for maintaining an edge for established and new players. Modularity emerges as a promising design feature enabling manufacturers to rethink how satellites are designed, built and operated, balancing reliability and performance with cost- and time-efficiency required in the new paradigm. Beyond operational efficiencies, modularity unlocks new strategic capabilities that enable satellite manufacturers to respond to shifting market demands (e.g., configurations for different customer needs) and proactively propose innovative solutions (e.g., new advanced services). However, the future direction of modularity adoption in satellite design remains unclear. While the literature offers numerous technically-oriented studies proposing various modularization approaches, many have struggled to gain widespread adoption. The barrier seems less in engineering feasibility and more in the lack of understanding of the broader modularity evolution in satellite architectures, questioning how modularity adoption evolves, which pathways dominate, and what forces shape this evolution. This paper addresses this gap by examining possible trajectories of modularity evolution in satellite design.

The study adopts an explorative abductive research approach, combining retrospective and forward-looking investigation. Secondary data (e.g., scientific literature, industry reports, patents) are used to trace the historical evolution of modularity and identify key design decisions and milestones that have shaped its adoption to date. To explore future possibilities, a multiple case study approach is used to provide insights into where modularity adoption heads next, showing critical decision points, enabling mechanisms, and potential lock-ins. The analysis highlights two distinct but interconnected trajectories shaped by gradual software-hardware decoupling, where modularity enables new software-driven (e.g., dynamic resource allocation) and hardware-driven (e.g., on orbit servicing) capabilities. We examine the technological, market, regulatory, and institutional forces shaping these trajectories and offer a strategic perspective on the future of satellite modularity. This paper contributes to the literature by bridging satellite engineering and technology management perspectives to understand better satellite design evolution. We propose insights for industry stakeholders that guide the development of adaptable and scalable satellite architectures, aligning with the broader goals of sustainable future space utilization.