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Space architecture for MoonVillage☆

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A B S T R A C T

The concept of a multinational MoonVillage, as proposed by Jan Wörner of ESA, is analyzed with respect to diverse factors affecting its implementation feasibility: potential activities and scale as a function of location, technology, and purpose; potential participants and their roles; business models for growth and sustainability as compared to the ISS; and implications for the field of space architecture. Environmental and operations constraints that govern all types of MoonVillage are detailed. Findings include: 1) while technically feasible, a MoonVillage would be more distributed and complex a project than the ISS; 2) significant and distinctive opportunities exist for willing participants, at all evolutionary scales and degrees of commercialization; 3) the mixed-use space business park model is essential for growth and permanence; 4) growth depends on exporting lunar material products, and the rate and extent of growth depends on export customers including terrestrial industries; 5) industrial-scale operations are a precondition for lunar urbanism, which goal in turn dramatically drives technology requirements; but 6) industrial viability cannot be discerned until significant in situ operations occur; and therefore 7) government investment in lunar surface operations is a strictly enabling step. Because of the resources it could apply, the U.S. government holds the greatest leverage on growth, no matter who founds a MoonVillage. The interplanetary business to be built may because for engagement.

1. Introduction

In 2015 Jan Wörner, Director General of ESA, introduced an idea called "MoonVillage" into the international conversation about destinations and purposes for human space flight [1]. Simply put, multiple nations and companies would bring systems and perform self-determined operations at a common location on the Moon, so that they all could benefit from the synergy of collocation, shared services, and economies of scale.

Wörner is quick to note that this is one suggestion for how to move humanity forward in lunar activities; that its primary purpose as a meme is to be a conceptual catalyst for conversation, concept formulation, and strategy making; and that a measure of progress would be supplanting the meme with a "better" one. Indeed, no single lunar location could enable all potential uses and users, so a singular MoonVillage cannot be universal. However, the idea has generated some traction as originally proffered [2–4].

What are the implications for space architecture of such a mixed-use, multi-player concept as MoonVillage – for site planning, systems, operations, outfitting, technical support, and the other manifold considerations of space architecture?

This paper explores how implementation and growth of MoonVillage space architecture might fit into the known framework of lunar surface conditions, the evolving framework of national and commercial interests for lunar activities, emergent knowledge about lunar science and resources, and the literature about mixed-use space infrastructure. Issues of scale and technology type as a function of population size, activities, and location on the lunar surface reveal principles for how a MoonVillage could work and be built, and the enabling capabilities for this to happen.

2. MoonVillage as a mixed-use space business park

Concepts for lunar colonies over the first half-century of space flight have tended toward one of three general types: scientific base; mining settlement; lunar city [5,6].

While useful as archetypes, single-purpose concepts are an impractical model for large-scale development of lunar activities. The most apt evidence for this conclusion is the historical contrast between vision and reality for Earth-orbiting space stations. Both Mir and Space Station Freedom were conceived as microgravity research laboratories whose development and utilization was to be funded by single governments. Because of Freedom's ambition (and hence, expense), it saw fruition as the International Space Station only once broadened into a multinational project, albeit still with an almost singular research purpose [7]. And today, just five years after assembly-complete, its continued existence beyond 2024 appears to hinge on viable planning for a transition to commercial ownership and operation as its patron governments shift their investments outward, beyond Earth orbit [8]. Options are under

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Nomenclature

CHNPS	Carbon, Hydrogen, Nitrogen, Phosphorus, Sulfur
CNSA	Chinese National Space Agency
EM-L1	Earth-Moon Lagrange Point 1
ESA	European Space Agency
GDP	Gross domestic product
ISS	International Space Station
KREEP	Potassium, Thorium, Rare Earth Elements, and Phosphorus
LED	Light emitting diodes
LEO	Low Earth orbit
NRC	National Research Council
RSA	Roskosmos
SSP	Space solar power

discussion now.

However, the end of Mir provides a sobering precedent: commercial viability of an aging, habitable, single-purpose orbital asset, transitioned to applications other than fundamental research, is not assured [9]. Obstacles for a successful transition from government-funded, fundamental-research laboratory to commercially-viable operations facility include: high capital costs for extending life as the asset ages, exacerbated due to the expertise oligopoly held by the asset's industrial developers; "overkill" requirements compared to the needs of diverse non-research users, which inflates sustainment costs; "closed" architecture resulting from cost-based compromises during development, that limit retrofit flexibility needed for the transition.

An alternative model was proposed in the literature in the early 1990s, even before Zvezda, the first ISS module, was launched and while Mir was still in its operational heyday: the mixed-use business park [10–12]. A *mixed-use space business park* would adapt well-understood terrestrial business real estate practices, facilitating from the start the economically viable establishment and growth of diverse spacefaring enterprises. Individual enterprises invest only in the unique capabilities, equipment, and materiel they need respectively; each pays fees for transportation and facility services, thereby buying the opportunity and freedom to innovate. The business park itself develops, owns, and operates the common facility (just as transportation providers own and operate their vehicles), taking on the financial risk of securing and sustaining user tenants. Individual tenants' business cases can close because they are spared the otherwise insurmountable infrastructure costs (a traditional role of government investment in opening new market areas). In turn, the facility's business case can close by avoiding the need to be engaged, expert, or successful in highly specialized space-utilization enterprises.

No single enterprise bears the full burden of driving all facility requirements; thus no single use type (e.g., fundamental research) dominates the architecture, capabilities, capacity, or operating costs (this is where the business park model differs from the model of adapting a laboratory like ISS). Standard, common-denominator services provide tenants a predictable operating environment, e.g., for security, utilities, and leases, all of which are essential for them to obtain their own financing. While reconciling the requirements of diverse activity types is not easy, tenant diversity provides a robust business base for the business park. Individual tenants' businesses may grow or fail, but the facility's own business case, based on a portfolio of tenants, goes on.

The published concept of an Earth-orbiting, mixed-use space business park can be adapted to the Moon, and thus be relevant to MoonVillage. At first, this might appear self-evident – were the model to be applicable independent of location. But it is not. Specifically, asteroids are untenable locations for this model because each is an astrodynamically singular site, and the only potential commercial business is mining. Mining colonies perhaps, but business parks, not foreseeably. And Mars is an untenable near-term location for the model because the economics of high-capacity interplanetary transportation favor the Moon, essentially forever.

To a lesser degree than LEO, but more than these other deep-space destinations, the Moon proffers multiple opportunities of potential interest to diverse pioneers: scientific, governmental, and commercial. Only "three days away," the Moon is in fact the next destination aspiration for many of the spacefaring organizations discussed next.

3. MoonVillage players

Deep into humanity's second half-century of space flight, many capable "players" have set their sights on the Moon in a contemporary redux of what motivated the first "space race": the Moon is a routinely visible, tangibly close, but technologically challenging destination. Reaching it demonstrates space flight prowess; and operating there routinely could open opportunities. Loosely grouped, there are three types of players capable of bringing resources to bear, who are interested in lunar activities today:

3.1. *Group I – the "big four" government spacefarers.*

Three government programs – based in Russia, the USA, and China – have operated on the Moon already, and ESA probably could if it chose to. Each major government player is subject to unique pragmatic constraints. Only the USA has ever achieved human lunar surface missions; but presently it cannot and does not plan to. Both Russia and China have operated roving robots on the lunar surface. Russia is perennially constrained financially, and has recently converted its space agency into a state corporation and announced a 30% reduction in decadal funding [13,14]. China presented its human lunar strategy in 2015 [15]. All four powers have large-scale space flight enterprises capable of building, launching, and operating habitable lunar spaceflight systems. This means that if motivated, *any of these four could competitively or collaboratively match projects undertaken by the others; or overtake activities pioneered by players in the other groups.*

3.2. *Group II – emergent and supporting government spacefarers.*

Many other government space flight programs – including those of Japan, Canada, India, Korea, Brazil, and the United Arab Emirates – demonstrate some combination of interplanetary or lunar orbital mission experience, partnership experience on the ISS, launch experience, lunar mission ambitions and projects, and related interplanetary mission capabilities. None has the capacity individually to motivate or establish a MoonVillage. But because they all use space flight as a catalyst for technological innovation, public inspiration, and demonstration of prowess, *they would tend to actively seek niche involvement in multinational lunar activities opened by or led by others*, each according to their unique expertise (e.g., Canadian robotic manipulators) or strategic goals (e.g., Japanese autonomous landing). Niche roles would exist for scientific-instrument expertise historically funded by national governments in Europe and Russia.

3.3. *Group III – industrial spacefarers.*

Various public and private space companies have an expressed or latent interest in lunar activities. The diacritical subgroups are "oldspace" and "newspace."

Oldspace companies tend to have established relationships with traditional government customers, and established supply-chain networks. Responsibility to shareholders and business inertia constrain them to follow their customers' money and interests, including lunar activities that may be pursued by Groups I or II.

Newspace companies tend to be motivated by a combination of