Lunar Architectures

Paul D. Spudis
Lunar and Planetary Institute

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What is an architecture?

A series of payloads and missions, laid out in a sequence to achieve some strategic goal or capability

Design choices are made, at least at a conceptual level

Should be flexible enough to adapt to changing technical requirements, budgetary issues and political undercurrents
Previous Lunar Architectures
1. Wernher von Braun’s *Das Marsprojekt* (1950)

Objective: Develop capability for Earth orbital, lunar and planetary spaceflight

Strategic Approach: Incremental, launch vehicle, Earth orbital station, Moon tug with cis-lunar capability, interplanetary flight

Tactical implementation: reusable launch vehicle, rotating space station in 1000 mile polar orbit, lunar tug with lander variant, Mars spacecraft

Alternatives: none
Previous Lunar Architectures

2. The Apollo Program (1961)

Objective: Within current decade, land man on the Moon and return him safely to the Earth

Strategic Approach: Build mega-rocket to fly complete mission in one or two launches (specific refutation of step-wise, incremental approach previously advocated by von Braun)

Tactical implementation: Saturn V (120 mT to LEO), Lunar Orbit Rendezvous mission profile (CM-SM-LM)

Alternative: Soviet N-1 and Soyuz, Earth Orbit Rendezvous, one-man LK (failed)
Previous Lunar Architectures


Objective: Return to the Moon, “this time, to stay.”

Strategic Approach: Use technology and hardware base of Shuttle and SS Freedom to build OTV, staging nodes, lunar lander, lunar base

Tactical implementation: Shuttle-C, SS Freedom modules, OTV (RL-10 based).

Alternatives: Livermore “Brilliant Condoms” - inflatables launched on EELV and derived vehicles
Previous Lunar Architectures


Objective: Return to the Moon with goal of living and working there for increasing periods of time; prepare for future human Mars mission

Strategic Approach: Apollo-like: Ares V HLV to deliver fueled transfer stage, Altair lander, EOR with Orion, launched on smaller Ares I

Tactical implementation: Ares V (150 mT), Ares I (25 mT), Orion CM, Altair lander (50 mT), multiple lunar sorties, build up to Mars mission (staged from Earth)

Alternatives: Shuttle-derived (SM or in-line), EELV-serviced cislunar depots, robotic-human composite lunar base
So what are the difficulties?

**Understanding the mission**
- Biggest issue with VSE
  - “Consensus is the absence of leadership.” — Margaret Thatcher

**Resources - Trying to do too much with too little**
- Blank sheet designs vs. adaptation of existing capabilities

**Schedule pressure**
- Deadlines or not?
- Political and technical cycles

**Technology fetishism**
- Need high-tech widget before x can happen

**Hyper-conservative design ethic**
- Safety vs. management of reasonable risks

**Process valued more than results**
- The Cult of Management
Some architectural principles

Money
High initial upfront costs are undesirable
But similarly, back-ended mega-liens should also be avoided
Total program costs are less important than rates of expenditure

Schedule
In general, the longer an architecture, the greater the total aggregate cost
However, the rate of expenditure tends to be lower
Accomplish milestones at frequent intervals

Capability
Get technology development as a by-product of trying to do something
In broad terms, more new technology means more risk, greater aggregate cost, longer timescales (but greater capability at end)
The better is the enemy of the good enough
Some architectural principles

Goals and Objectives
What are you trying to do and WHY?
Multiple objectives make for a more costly, longer program
However, architecture focused on some narrow goal may be optimized for that goal but will not serve others adequately
“Destination-centric” is not the problem

Variables
Optimizing for one variable (e.g., Δv or mass) is a dumb strategy
Minimize number of branch points prior to attaining your objective, maximize them after you achieve it
Launch vehicle choice dictates strategic approach (heavy lift vs. depots)
Re-thinking the architectural problem

Spaceflight is difficult
- The Tyranny of the Rocket Equation
- Reaching LEO with empty fuel tanks

Spaceflight is expensive
- Accelerating tons of mass to Mach 25, lifting it hundreds of km up along an extremely narrow (few meter) path for thousands of km downrange is a very hard task
- Precision machining, complex avionics, difficult-to-work materials

Spaceflight is barely possible
- If radius of Earth were 50% larger, the energy in chemical bonds would not be sufficient to reach orbit

The benefits of spaceflight are not intuitively obvious
- Human destiny, species survival, “Because it’s there..” are not typical justifications for massive amounts of federal spending
Or to put it another way…

Our ultimate goal in space is to go anywhere, anytime with as much capability as we need.

Spacecraft are mass- and power-limited and thus, capability-limited.

They will remain so as long as we are restricted to what can be lifted out of Earth’s gravity well.

This restriction negatively impacts scientific capabilities, economic health, and national security.

To extend reach and capability, we must learn to use what we find in space to create new space faring capabilities.
Cislunar Space: A New Strategic Arena?

Cislunar: the volume of space between Earth and Moon

**Zones of cislunar space**
- LEO, MEO, GEO, HEO, L-points
- Different assets located at different levels of cislunar
- Need freedom of movement for machines, people

Modern national strategic needs depend critically upon ability to use our satellite assets

Space power projection involves both protection of assets and denial of assets to an adversary
Lessons from Shuttle and Station Programs

Large, distributed systems too big to be launched from Earth can be assembled in space.

Humans and machines working together can assemble, service and maintain complex space systems.

Applying this paradigm to trans-LEO (cislunar) space requires development of a transportation system that is affordable, extensible, and reusable.

Developing the resources of the Moon enables the creation of such a system (if you can reach the Moon, you can access any other point in cislunar space).
Modern industrial civilization depends critically on numerous satellite assets in high orbits above LEO:

- GPS and navigation
- Global communications
- Remote sensing, weather
- Surveillance and national security assets

We cannot access those satellites to maintain them or to build large, distributed space systems.

If we could access those satellites with humans and robots, new capabilities from space assets could be created, ensuring ourselves a better quality of life, a bigger and stronger economy, and a more secure world.
Space faring: Changing the Rules

Current template
- Custom-built, self-contained, mission-specific spacecraft
- Launch on expendable vehicles
- Operate for set lifetime
- Abandon after use
- Repeat, repeat, repeat

New template
- Incremental, extensible building blocks
- Extract material and energy resources of space to use in space
- Launch only what cannot be fabricated or built in space
- Build and operate flexible, modular, extensible in-space systems
- Maintain, expand and use indefinitely
Goals and Principles

Extend human reach beyond LEO by creating a permanent, extensible space faring infrastructure

Use the material and energy resources of the Moon to create this system

Lunar return by small, incremental, cumulative steps

Proximity of Moon permits progress prior to human arrival via robotic teleoperations

Innovative space systems: fuel depots, robotics, ISRU, reusable spacecraft, staging nodes

Schedule is free variable; constant, steady progress but no deadlines
Architectural Implications

Use robotic flights to acquire strategic knowledge and emplace assets
- robotic missions are not just for science

Commonality of hardware, systems, procedures between robotic and human flight elements
- test human flight components on robotic missions

Locate “high grade” lunar resources and build human habitats nearby
- concentrated resources (e.g., polar ice) are easiest to use; focus on them first

Build up infrastructure in a single location to create capability rapidly
- Forget sorties: pick the site and build up an outpost
An Affordable Lunar Return Architecture


Mission
Create a permanent human-tended lunar outpost to harvest water and make propellant

Approach
Small, incremental, cumulative steps
Robotic assets first to document resources, demonstrate production methods
Assume water abundance of 10 wt.%
Teleoperation of robotic mining equipment from Earth. Emplace and build outpost assets remotely
Use existing LV, HLV if it becomes available

Cost and Schedule
Fits under existing run-out budget (< $7B/year, 16 years, aggregate cost $88 B, real-year dollars)
Resource processing outpost operational halfway through program (after 18 missions); end stage after 30 missions: 150 mT water/year production (break-even)

Benefits
Permanent space transportation system
Routine access to all cislunar space by people and machines
Experience living and working on another world
Initial Steps

1. Communication/navigation satellites
   Polar areas out of constant Earth LOS; need comm, positional knowledge

2. Polar prospecting rovers
   Study and characterize water deposits, other substances, environment

3. ISRU demo
   Heat icy regolith to extract water; purify and store as ice in cold traps

4. Digger/Hauler rovers
   Excavate regolith, transport feedstock to fixed stations for water extraction

5. Water tankers
   Purify and store extracted water
Next Steps

6. Electrolysis units
   Crack water into hydrogen and oxygen; liquefy into cryogens

7. Supporting equipment
   Robotic Landers - medium (500 kg payload), heavy (2 mT payload)
   Power plants - extendable solar arrays, steerable on vertical axis to track sun at poles
   Cryo storage - store LOX, LH$_2$ (use cold traps, 25 K)
   Material Fabricators - Process regolith for rapid prototype products and parts

8. Space-based assets
   LEO depot - fuel lunar departure stages
   LLO depot - staging node for reusable cargo and human landers
Outpost Layout Concept

- Water Ice Deposit
- Beacons
- HL Support Cart
- Human Lander (HL) Zone
- Blast Berm
- Regolith Waste
- Living Cluster
- Pressurized Transfer Vehicle
- Unpressurized ISRU Lab
- Portable Communication Terminal
- Propellant Manufacturing Zone
- RWTL Zone
- RWTL Support Cart
- Habitation Zone
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| Water Production (MT/yr)                   | 10     | 50     | 50     | 50     | 50     | 100    | 100    | 150    | 150    | 150     |         |         |         |         |         |         |
| Propellant Production (MT/yr)              | 1      | 5      | 10     | 25     | 50     | 86     | 100    | 130    | 130    | 130     |         |         |         |         |         |         |
| Power Production (kW)                      | 25     | 50     | 50     | 50     | 50     | 100    | 100    | 150    | 150    | 150     |         |         |         |         |         |         |

*Color Legend:*
- **Lunar orbital**
- **Earth orbital**
- **Rovers**
- **Fixed stations**
- **Landers**
- **Human**
Augustine run-out budget
Program Summary

Create a permanent, cislunar space transportation system based upon the harvest and use of lunar water

Most infrastructure is emplaced and operated robotically; people come when facilities and budgets are ready

Small incremental steps that build upon each other and work together

Progress continually made, regardless of budgetary issues in any given year

Incremental approach greatly facilitates both commercial and international participation

Cislunar system created here is a “transcontinental railroad” in space, opening up the space frontier
Value Returned for Money Spent

Create an extensible, reusable cislunar space transportation system based around the use of the resources of the Moon

Such a space transportation system has the inherent capability to take us to the planets

Obtain a permanent foothold on another planetary body (the Moon) for the first time in human history

Develop the means to build large, high-power distributed space systems to serve a variety of national and international economic, scientific and security objectives

Become a true space-faring species; learning to use off-planet resources is the first step of settlement
Is it possible to devise a sustainable architecture for lunar return?

Yes

Incremental approach that reaches notable milestones on a recurring, continuous basis
Achieves some capability of recognized societal value
Leads logically to next step (no isolated accomplishments)

No

Political system makes space goals beyond 3-4 year time horizon untenable
Shrinking fraction of federal budget available for space
Panem et circenses mentality
Agency is not configured for a long-range, strategic program
What Kind of Space Program?

Two Visions

“A spectacular series of space ‘firsts’”
(Augustine report, 2009)
Launch, use and discard
Everything comes up from Earth
One-off, PR “stunt” missions
Accomplish the feat and cancel the program
Flags and footprints forever
Costly and subject to political and fiscal winds of change

Become a true space faring species
Reusable, maintainable, extensible space systems
Incremental, cumulative, steady progression outward
Fit under any budget envelope; return value for money spent
Government develops and demos technology; commerce follows
Create a permanent and expanding space transportation infrastructure
Less glitter, more substance
Space – A New Rationale

“If God wanted man to become a space-faring species, He would have given man a Moon.”

Krafft Ehricke

**Explore** to broaden our knowledge and imagination base

**Prosper** by using the unlimited energy and materials of space to increase our wealth

**Secure** our nation and the world by using the assets of space to protect the planet and ourselves