Federated Simulation and Gaming Framework for a Decentralized Space-based Resource Economy

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ABSTRACT

Future human space exploration will require large amounts of resources for shielding and building materials, propellants, and consumables. A space-based resource economy could produce, transport, and store resource at distributed locations such as the lunar surface, stable orbits, or Lagrange points to avoid Earth's deep gravity well. Design challenges include decentralized operation and management and socio-technical complexities not commonly addressed by modeling and simulation methods. This paper seeks to tackle these challenges by applying aspects of military wargaming to promote effective communication between decision-makers. A software architecture for federated simulation based on IEEE-1516 (HLA-Evolved) is presented in the context of multiple lunar *in-situ* resource production processes, resource depots, and intermediate transportation. The federation-level framework identifies interfaces between simulation models (federates), focusing on persistent assets (elements) and resources exchanged. Future work will develop the federated resource economy model and evaluate with decision-makers playing the roles of competing and collaborating players.

INTRODUCTION

A key challenge in future human space exploration is accommodating resources to sustain human life and operations at distant locations. The major sources of mass in exploration include propellant, habitats and radiation shielding, and consumables. Even with advantages of partially-closed environmental control systems and some propellant production on the Martian surface, NASA Design Reference Architecture 5.0 (chemical propulsion variant) requires twelve heavy-lift (120 metric ton) launch vehicles (Drake, 2009). This expense is due to the energy required to transition between deep gravity wells – each kilogram making the round-trip journey requires over 200 kilograms of propellant (see Appendix for details).

One approach to reduce the cost of exploration is to limit the burden of logistics supply from Earth's surface. In particular, a distributed set of systems could collaborate in a space-based economy focused on the production, transportation, and storage of critical resources such as water, oxygen, or energy at intermediate locations such as the lunar surface, stable orbits in cis-lunar space, or Lagrange points (Ishimatsu, 2011). Aside from technical feasibility, decentralized control and the socio-technical complexities involved make this concept challenging to architect.

There is active interest in enabling multi-national and commercial enterprises supporting future space exploration (Griffin, 2011). In part, these ventures will be competitive (e.g. national prestige or commercial contracts), but they will also be collaborative given the high costs and complexity of space exploration. Within the scope of a space-based resource economy, there could be many organizations responsible for distributed component systems (see Table 1).

Table 1. Space-based Resource Economy Components

Component	**Purpose**	**Example(s)**
Human exploration mission	Advance knowledge by exploring new and distant locations.	Vostok 1 (RKA), Apollo 11 (NASA), Shenzhou 5 (CNSA)
Launch vehicle	Transport humans or resources from Earth's surface to orbit.	Delta IV (ULA), Falcon 9 (SpaceX), Proton M (RKA)
In-space vehicle	Transport humans or resources between locations in space.	Cygnus (Orbital), HTV (JAXA), ATV (ESA)
Habitat/depot	House humans or store resources in space or on a planetary surface.	Zvezda (RKA), Shenzhou-Tiangong (CNSA)
Descent/ascent vehicle	Transport humans or resources between the surface and space.	Soyuz (RKA), Lunar Module (NASA)
Surface vehicle	Transport humans or matter between surface locations.	Lunar Rover (NASA), ATHLETE (NASA)
Communications link	Transfer information between locations.	CDSCC (Deep Space Network), DirecTV-10 (DirecTV), USA-164 (Milstar)
Resource plant	Produce or transform resources.	*In-situ* resource production, Solar arrays, Fuel cell

A space-based resource economy fits the two distinguishing characteristics of system-of-systems: operational and managerial independence of the components (Maier, 1998). Operational independence, the ability for each component system to operate if disassembled from the larger system, is inherent to the large time and distance scales involved in space exploration. Managerial independence is illustrated by multi-national and commercial entities with no single organization having absolute authority. A key challenge of architecting a system-of-systems is the lack of central control in the component system design and operation.

A space-based resource economy is also classifiable as a complex, large-scale, interconnected, open, and socio-technical (CLIOS) system (Dodder, 2003). Although the spacecraft and resource systems are complex (internal complexity), as are the interactions within and between systems (behavioral complexity), there are also significant social complexities. In particular, the stakeholders developing each component system exhibit preferences motivated by their own value proposition (evaluative complexity) and their decisions exist within a larger, institutional sphere of policy and inter-organizational dynamics (nested complexity). These four aspects of complexity are illustrated in Figure 1.

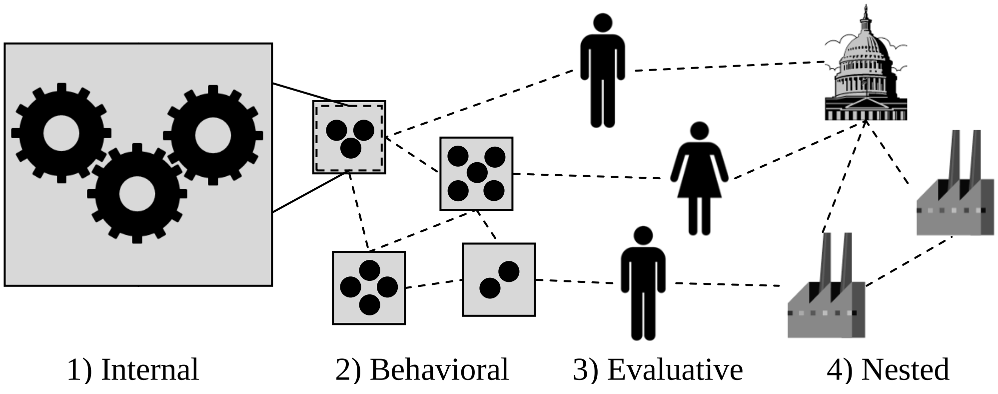

Figure 1. Complexities in CLIOS Systems

Influencing future space exploration will require sophisticated planning and, without resources to experiment and prototype with real systems, models play an important role. Interactive simulation and gaming solicits the participation of human decision-makers to allow the consideration of both technical (internal and behavioral) and social (evaluative and nested) complexities. To support this concept, we look to the use of simulations and games within a related domain: the military.

WARGAMING AND FEDERATED SIMULATION

Military planning and strategy is an ancient field of study aided in modern times with the application of science and computation. Wargaming provides decision-makers with an integrated experience to learn and discuss decisions without the cost or risk of live field exercises. It is differentiated from technical analysis in that, although rigorous physics-based and empirical models are incorporated, wargaming will not produce a "quantitative or logical dissection of a problem" but, rather, is "an exercise in human interaction, and the interplay of human decisions" (Perla, 1990:164). Wargames are described as "a unique forum for communicating ideas in vivid and memorable ways, and for discussing the validity and applicability of those ideas in a more empirical and less abstract way" (Perla, 1990:9). Thus, wargames support effective communication, a contributing factor to system-of-systems design, which is described as "an exercise in communications architecting" (Maier, 1998).

Military systems have similar characteristics to a space-based resource economy: both are system-of-systems having strong social and technical complexities. Although space exploration doesn't have a clear antagonist, natural uncertainties and the balance between cooperation and competition between players is a source of conflict. More broadly, the definition of a *game* as "an activity among two or more independent decision-makers seeking to achieve their objectives in some limiting context" (Abt, 1970), fits the type of problem we seek to investigate and applying the designs of wargames may be beneficial.

There are a wide variety of wargaming designs, one being the computer-assisted wargame in which human players presented with a scenario make decisions and software models support the propagation of effects in time and space. Federated simulation allows multiple system simulations (federates) to be developed independently with encapsulated details, mirroring the decentralized design and operation of a system-of-systems. HLA-Evolved (IEEE Std. 1516-2010) is a software architecture for federated simulation, developed for the military but recently applied to other domains including space exploration (Essilfie-Conduah et al., 2011).

A federated simulation consists of multiple federates exchanging data over an information network, illustrated in Figure 2. Data formats for encoding and decoding complex data types and high-level behaviors and regulations are defined in a federation agreement. Network-level communication is managed by a runtime infrastructure (RTI), a software application provided by a vendor that implements the requirements of the HLA-Evolved standard. Each federate sends and receives data through an application-level interface managed by the local RTI component (LRC). A central RTI component (CRC) manages federation-level processes such as time management and message routing.

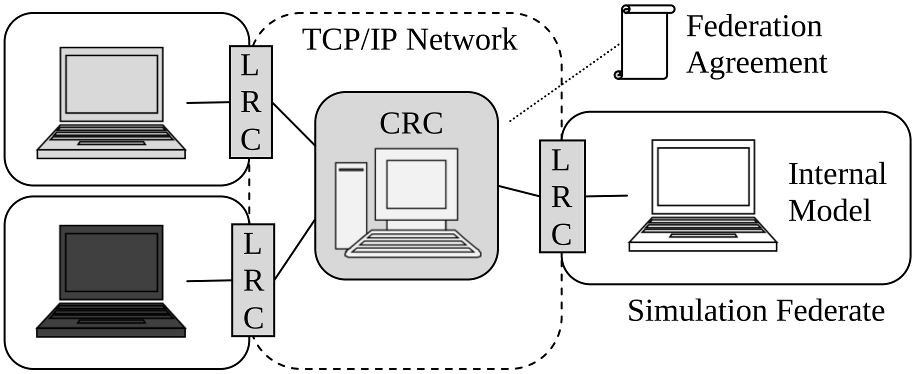

Figure 2. HLA-Evolved Federated Simulation

Coupled with human interaction, federated simulation addresses both decentralized authority and socio-technical complexities inherent to each player associated with a space-based resource economy. Using concepts drawn from military wargaming and other modeling exercises, this paper seeks to address the following question:

> What federation-level modeling framework or architecture captures the interfaces between constituent systems within a space-based resource economy?

First, to frame this question, we present a potential application case of federated simulation and gaming in developing a space-based resource economy with *in-situ* resource production on the lunar surface.

APPLICATION CASE

Having lower gravity than Earth, the Moon may be a source of resources to support an economy. There is evidence that the lunar surface contains adequate quantities of critical resources such as silicon and iron metal oxides, water-ice, hydrogen, and exotic fuels like helium-3. Moreover, resources can be transformed to other forms with thermal and electric energy by several processes described in Table 2.

Table 2. *In-situ* Resource Transformation Processes

Process	Basic Formula	Notes
Sabatier Reaction	$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$	Elevated temperatures, Exothermic
Bosch Reaction	$CO_2 + 2H_2 \rightarrow C + 2H_2O$	Elevated temperatures, Endothermic
Electrolysis	$2H_2O \rightarrow 2H_2 + O_2$	Electricity required
Hydrogen Reduction	$MO_x + H_2 \rightarrow M + H_2O$	Elevated temperatures, Endothermic
Carbothermal Reduction	$MO_x + CH_4 \rightarrow M + CO + 2H_2$	Elevated temperatures, Endothermic
Methanation Reactor	$CO + 3H_2 \rightarrow CH_4 + H_2O$	Elevated temperatures, Exothermic

Given the processes available at a particular time, some resources are demanded as inputs and others are produced as outputs. Coupled with the demands for propellants (O_2 and possibly H_2 or CH_4), human consumption (O_2, H_2O, and hydrocarbons) and waste (CO_2, H_2O, and hydrocarbons), and habitat and shielding (Fe, Si, and H_2O), there are many potential resource economy architectures and deployment sequences.

As illustrated in Figure 3, systems contributing to the resource economy include launch vehicles, in-space and ascent-descent transportation, *in-situ* processing plants, and resource depots such as at the first Earth-Moon Lagrange point (EML1).

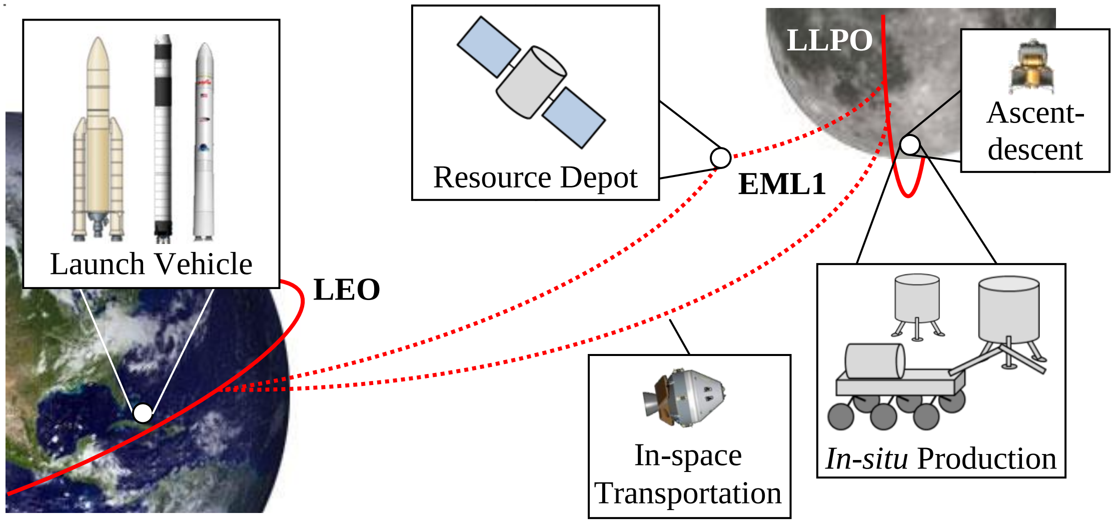

Figure 3. Lunar *in-situ* Resource Production Components

The design of each constituent system may have a large impact on the overall system-of-systems. For example, consider the selection of ion versus chemical-based in-space propulsion. Ion propulsion is much more efficient, though slower; however chemical engines could be refueled by the same propellant being produced. Additionally, there may be policies or incentives to promote collaboration where it is otherwise voluntary and not in the self interest of a particular player.

Lifecycle properties such as availability or reliability of individual systems may also affect the overall performance of the resource economy, especially under uncertainty. If a resource production plant requires frequent human maintenance, demands from workers could overwhelm its resource production.

Questions pertaining to the decentralized authority and socio-technical complexities addressed by a simulation and gaming approach for this scenario include:

- What phases of build-up (staged deployment) can contribute to stable intermediate forms of a resource economy?
- Are there key technologies, cost levels, or incentives that provide a tipping point for the viability of a resource economy?
- How do availability and reliability of *in-situ* processing plants influence the function of a resource economy?

To answer these questions, players would control simulation federates from the perspective of participating organizations. Repeated simulation executions coupled with discussion with other players would result in insights to the dynamics of the socio-technical system-of-systems and strategies for effective decisions. Similar to scenario analysis, games could target decisions made under different possible futures including varying available technology levels, commercial launch vehicle costs, number of players, and relative resource value.

SIMULATION AND GAMING FRAMEWORK

At the federation level, a simulation and gaming framework describes the interfaces between participating federates. Following the HLA-Evolved software architecture, it includes data models (attributes and parameters), object models (persistent entities), and interaction models (transient events). This division of models is discussed in the context of two related frameworks: SpaceNet and a functional system classification.

SpaceNet is a discrete event simulation tool for space exploration logistics analysis (Grogan, 2010). Its modeling framework consists of a network (spatial locations and time-expanded connections), resources, elements, and events. The network and elements, both persistent entities in the simulation, correspond to object models. Resources are not uniquely determined (e.g. one doesn't know *which* kilogram of water is drawn from a tank), and are always attributes of another object (e.g. an element holds a quantity of resources), thus correspond to a data model. The events, of which there are seven core events (create, move, reconfigure, and destroy elements and add, transfer, and consume resources) correspond to interaction models.

As another example, a matrix-based functional classification describes complex systems using five processes (transform, transport, store, control, and exchange) acting on five operands (matter, energy, information, living organisms, and finances) (de Weck et al., 2011:38-43). In this classification, the operands correspond to object models and the processes correspond to interaction models. In particular, the transport, control, and exchange processes take place across federate boundaries whereas the transform and store processes would take place within a single federate.

Building on these concepts, the simulation and gaming framework uses data models for resources, object models for elements and players, and interaction models for events between federates such as resource exchange and transportation of elements.

The *resource* data model includes the amount and type of resource represented (e.g. water, oxygen, or more abstract based on a class of supply such as "consumables"). As a data model, resources exist as attributes of objects or parameters of interactions. Some resource types, such as electricity or money, are not measured in mass-based units, so each resource should also define its units of measurement. Examples of resources include 7.1 kilowatt hours of electricity, 2.0 kilograms of consumables, and 1.2 liters of water.

The *element* object contains an attribute identifying the quantity of resources it contains. For example, an in-space vehicle may contain propellant available for propulsion, which may be decreased during a burn or increased upon refueling refueled during a simulation. Other elements may internally transform between types resources to change their contents – an electrolysis system may start with a quantity of water and over time transform it to oxygen and hydrogen.

Since a player may command more than one element under a particular organization, a *player* object maintains the account balance measured in monetary resources. Any monetary resources exchanged by a player's elements are transferred to the account balance. Some scenarios may also use an *environment* object, controlled by a non-player federate, to identify attributes external to the resource economy boundary, such as market prices, resource concentrations, or natural effects.

Interaction models must be negotiated between players as a two-step request and response process. One player requests an interaction, and only if the other responds affirmatively, does the interaction take place. The *element transport* interaction describes the transportation of elements to a destination by a carrier, such as performed by a launch vehicle, in exchange for resources. The *resource exchange* interaction describes the simultaneous exchange of resources between two co-located elements. For example, a resource exchange at a propellant depot may trade propellant for money. Within this framework, interactions occur instantaneously, however given additional parameters, transports and exchanges may be scheduled for repeated, or multiple executions.

CONCLUSION

A space-based resource economy seeks to establish a decentralized system-of-systems to produce, transport, and store resources to reduce the logistics burden of future space exploration. Design challenges include decentralized authority of the constituent systems and socio-technical complexities of multi-national and commercial ventures, motivating new methods and tools to evaluate concepts in an integrative way. Federated simulation, developed in the military domain and applied through wargaming, inherently models a system-of-systems, and when coupled with human players, can promote effective communication between decision-makers addressing some of the social complexities in the design of a resource economy.

The federation-level simulation and gaming framework consists of data, object, and interaction models to capture the resources, players and elements, and interactions between federates taking place during the simulation. Future development will seek to develop federate-specific models and a federation agreement based on the application case of a lunar *in-situ* resource economy. Individual federate models will include launch vehicles, in-space and ascent-descent transportation, resource depots, and resource production plants using multiple transformational processes.

As the framework is matured through application cases and prototypes, an application programming interface (API) will be developed to provide shared functionality such as data structures and logical validation per the federation agreement across the individual federates to simplify their development. Beta testing with volunteer subjects and a simplified scenario based on the lunar *in-situ* resource economy is targeted for spring 2012, followed by more detailed scenario development and evaluation using representative players in the summer and fall 2012.

The challenging of developing an infrastructure system-of-systems is not limited to the domain of space exploration. Indeed, human exploration to remote destinations can be seen as the ultimate test of *sustainability*, a rich topic in earthbound civilization. The objective of future work is to extend the modeling framework to terrestrial domains as a method of “strategic engineering gaming,” specifically targeting infrastructure system-of-systems.

ACKNOWLEDGMENTS

This research is funded with government support awarded by DoD, Air Force Office of Scientific Research, National Defense Science and Engineering Graduate (NDSEG) Fellowship, 32 CFR 168a.

APPENDIX: PROPELLANT RATIO CALCULATION

To find the mass of propellant to transport one unit of mass along a transport segment we define the propellant-to-mass ratio, r shown in Eq. (1):

$$r \equiv \frac{m_0 - m_1}{m_1} \tag{1}$$

where m_0 is the initial stack mass, and m_1 is the final stack mass. Using the ideal rocket equation, shown in Eq. (2):

$$\Delta V = I_{sp} g_0 \ln \frac{m_0}{m_1} \tag{2}$$

where I_{sp} is the rocket specific impulse, g_0 is the gravitational acceleration at Earth's surface (i.e. 9.81 m/s^2), and ΔV is the desired change in velocity, we can rearrange to solve for r, shown in Eq. (3):

$$r = e^{\Delta V / g_0 I_{sp}} - 1 \tag{3}$$

The cumulative propellant-to-mass ratio, R, for a sequence of transports $\{1 \ldots N\}$ is found using Eq. (4):

$$R = \prod (r_i + 1) - 1 = \prod \left(e^{\Delta V_i / g_0 I_{sp,i}} \right) - 1 = e^{\sum \Delta V_i / g_0 I_{sp,i}} - 1 \tag{4}$$

The round-trip journey between Earth and Mars is comprised of six phases, shown in Table 3. Each phase has a ΔV determined by astrodynamics and an I_{sp} determined by vehicle design. The launch has three stages with varying I_{sp}, and approximate ΔV split: PBAN first stage (270 s), LOX/LH$_2$ second stage (415 s), and LOX/LH$_2$ upper stage (450 s). The in-space phases use LOX/LH$_2$ engines similar to the upper stage (450 s) and the ascent and descent phases use LOX/LCH$_4$ engines (370 s).

Table 3. Mars Mission Propellant-to-Mass Ratios

i	Mission Phase	ΔV (m/s)	I_{sp} (s)	r (-)	R (-)
1	Earth Launch (3 Stages)	9800	-	11.15	230.8
1.1	*First Stage*	*1200*	*270*	*0.56*	*11.1*
1.2	*Second Stage*	*5100*	*415*	*2.51*	*6.8*
1.3	*Third Stage*	*3500*	*450*	*1.21*	*1.2*
2	Earth Departure (TMI)	4100	450	1.53	18.1
3	Mars Arrival (MOI)	1700	450	0.47	6.5
4	Mars Descent	600	370	0.18	4.1
5	Mars Ascent	4100	370	2.09	3.3
6	Mars Departure (TEI)	1500	450	0.40	0.4

The resulting cumulative propellant-to-mass ratio is about 230. Alternative designs using nuclear thermal rockets (NTRs) for in-space transport (achieving specific impulses between 875-950 s) and aerobraking in lieu of a Mars arrival burn could reduce the cumulative propellant-to-cargo ratio for a Mars mission to about 80, however these options also have higher costs of fuel and vehicles.

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