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An Evolutionary Computation System Design Concept for Developing Controlled Closed Ecosystems

An Intelligent Systems Approach to Foster Gravitational Ecosystem Research for Developing Sustainable Communities in Space and on Earth

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November 2018

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Introduction

Figure 1: Apollo 8: Earthrise - December 24, 1968

This paper describes the design concept and preliminary design details of the Controlled Closed-Ecosystem Development System (CCEDS) that uses Evolutionary Computation (EC) for developing Closed EcoSystems (CESs) that are externally controlled.

As shown in figure 1 from the vantage point of the Moon, the Earth's biosphere is the most sophisticated complex adaptive system known to exist in the entire universe and has persisted for over 4 billion years. A complex adaptive system is a network of interacting adaptive systems whose nonlinear dynamics and emergent behaviors are difficult to predict and control; therefore for such systems, past performance is no guarantee of future results, which is particularly the case for the Earth's biosphere during a period of exponential technological growth. The scientific study of the Earth's biosphere traces back to Vladimir Vernadsky and his work "The Biosphere," in which among other things he made the case that life continuously transforms the geochemistry of the planet and in turn is so transformed (Vernadsky, 1926).

The value proposition for this CCEDS is that it develops designs for sustainable, small-scale reproductions of subsets of the Earth's biosphere that can be distributed both on and beyond Earth, for improving the quality of life for all life, expanding the diversity of life, studying and protecting life, as well as enabling life to permanently extend beyond Earth. Although the minimum size of a CES that reliably persists indefinitely is unknown, the preeminent, long-term goal of this effort is to develop CESs that enable human populations to persist indefinitely independent of their locations on Earth and beyond. A hypothesis potentially to be tested by the CCEDS described in this paper is: can small, completely-independent reproductions of subsets of the Earth's biosphere, containing populations of microbes, plants, animals, and eventually people, thrive indefinitely? Even if the hypothesis cannot be proven, the effort will increase our understanding of the ecosystems we live in so they can be more verdant, diverse, and effectively managed.

Although this paper focuses on an EC machine learning approach for developing controlled CES complex adaptive systems, the approach can be generalized to use a wide range of machine learning algorithms for the adjustably-autonomous development of complex adaptive systems. The study of complex adaptive systems in general is summarized in (Holland, 2005).

Closed Ecosystems (CESs)

CES Overview

For the purpose of this paper, a CES is a community of organisms and their resources that persist in a sealed volume such that mass is not added or removed. The effects of radiation on a CES can be considerable, but the minute amounts of CES mass added or removed due to radiation do not disqualify a sealed volume from being a CES. The mass (food/air/water) required by the CES organisms is continually recycled from the mass (waste) produced by the organisms. Energy and information may be transferred to and from a CES. CESs that can support mammals indefinitely remain speculative (other than the Earth itself, which is only partially closed). The combinations of minimum required mass, volume, and species (recipes) for mammalian CESs are unknown, but are expected to be miniscule compared to the Earth.

A Partially Closed EcoSystem (PCES) permits the limited addition and removal of mass. The extent to which an ecosystem is partially closed can run the gamut from being almost entirely closed, e.g., permitting the medication and extracting organic samples, to being almost entirely open where CES mass addition and mass removal events are significant, frequent, and uncontrolled. The computational approach described in this paper focuses on CESs, but many of the techniques and models developed are applicable to PCESs, particularly those in which the mass added and the mass removed are tightly controlled.

To generate data for the CCEDS and to test CES models generated by the CCEDS, a group of small CESs are being planned that generate data without direct human interaction and that are continually optimized by the CCEDS by modeling the CESs based on the data they produce. Small CESs can be combined and/or expanded to very large sizes. The hypothesis to be tested is that these CESs can be made large enough and persist long enough to support human populations enabling people to live sustainably almost anywhere on Earth with much lower impact on each other and other life.

Human-Occupied CES Goal

As depicted in figure 2, a human-occupied controlled CES would not require external sources of air, water, and food nor would it release any wastes.

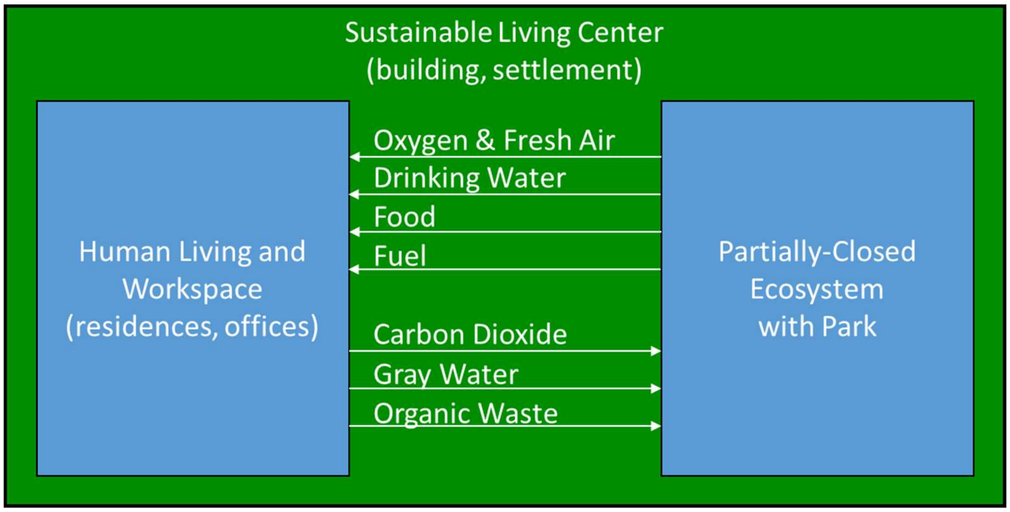


Figure 2: An Example of a Sustainable Living Center

Although efforts continue to be made toward this end (e.g., (Allen, Nelson, Alling, 2003) http://biosphere2.org/), significant challenges remain (e.g., Nelson, Dempster, Allen, 2013). For NASA, progress must be made to reach the CES level of capability that is nearly essential to achieve U.S. Space Policy Directive 1, which directs the NASA Administrator to “enable human expansion across the solar system” (Federal Register, 2017), due to the vast distances involved among other things.

CES Example

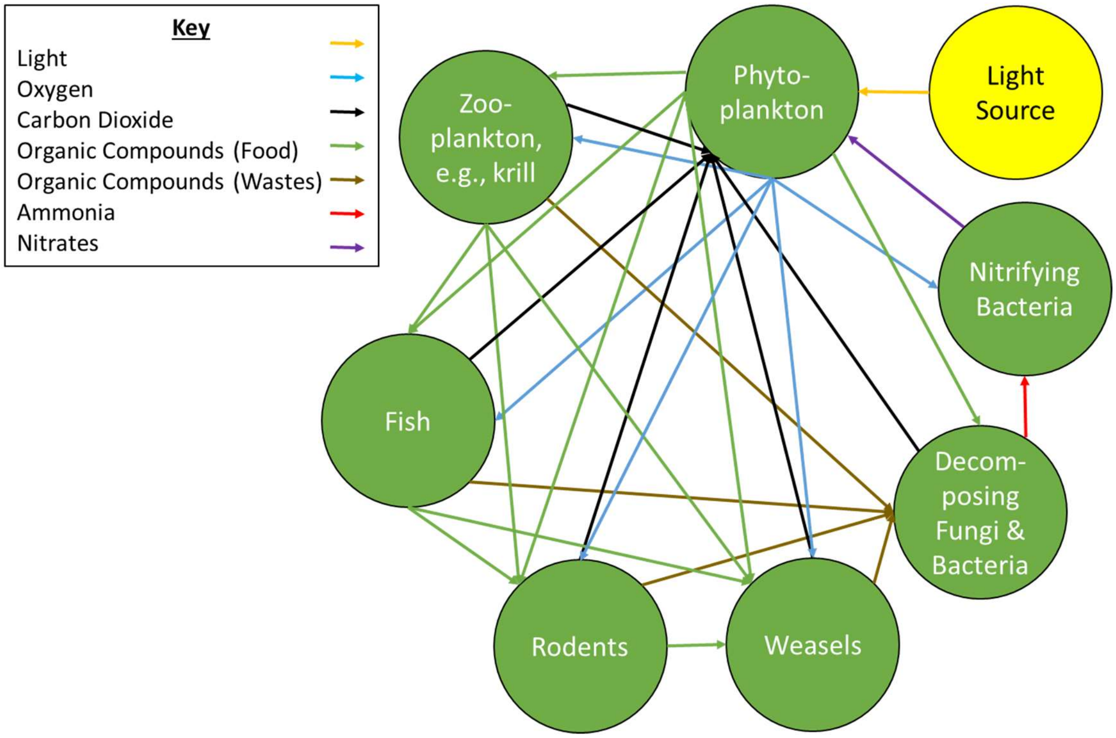


Figure 3: An Example of a Sample CES with Mammals and Aquatic Organisms

A CES can function with a wide range of species. Shown in figure 3 is an example of a CES that is partially terrestrial and partially aquatic. Phytoplankton, such as algae and cyanobacteria, use light, carbon dioxide, water, and other organic compounds to grow and reproduce releasing oxygen in the process. Zooplankton, such as krill, consume phytoplankton, oxygen, and other resources to grow and reproduce releasing carbon dioxide and wastes in the process. As zooplankton produce waste and eventually die, decomposing fungi and bacteria convert their remains and wastes to carbon dioxide and organic compounds closing the resource loops. Fish can be added that feed on phytoplankton, zooplankton, and other fish. Rodents can be added that feed on fish; and weasels can be added that feed on fish and rodents also closing resource loops as depicted in figure 3.

Biomes

CESs instantiate small, controlled-biomes and their environments. F. Clements and V. Shelford first defined the term "biome" essentially as a biotic community of plants and animals populating a region. They stated, "From the beginnings of life, organisms have lived together in some kind of grouping. ... We know now that there are no habitats in which both plant and animal organisms are able to live, in which both do not occur and influence each other." (Clements and Shelford, 1936, p. v).

Biome Dimensions

Throughout the world, similar plants and animals group together. In *Communities and Ecosystems* (Whittaker, 1975), R. Whittaker characterized several biomes, with respect to the mean temperature and mean precipitation, and summarized this analysis in a diagram of terrestrial biomes. A simplified version of Whittaker's diagram is shown in figure 4.

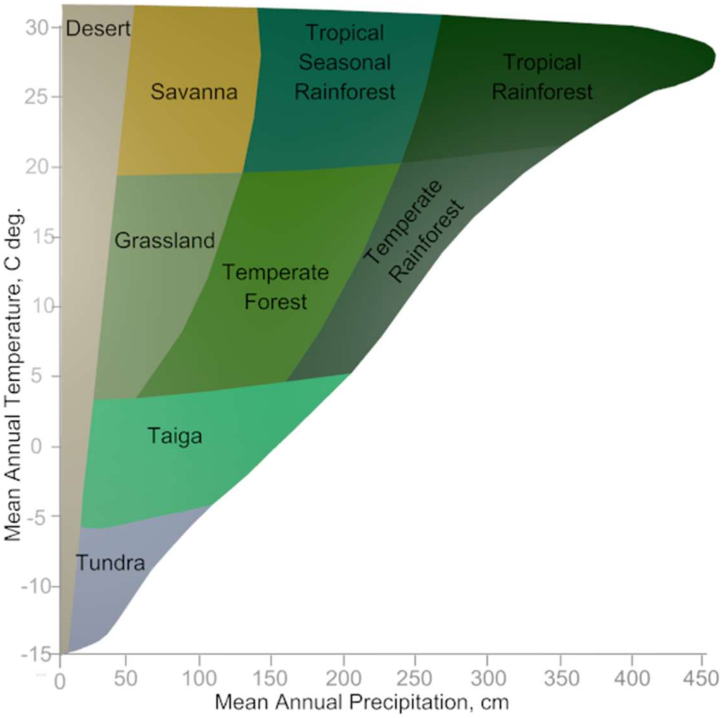


Figure 4: Whittaker Biome Diagram derivation (Whittaker, 1975)

The mean temperature and mean precipitation used by Whittaker in his analyses assumes that the Earth’s day-night cycles and annual season cycles regularly occur. CESs have the capability to create small biomes with the same mean temperature and mean precipitation, but could have drastically different results. Consider a biome where the mean annual temperature is 10°C and the mean annual precipitation is 150 cm, as is the case for Temperate Forests shown in figure 4, but the temperature is either above 100°C or below 0°C each day and all the rain falls only on one day a year. Such a biome would not foster life found in Temperate Forests. Similarly, if this biome’s temperature and precipitation rates are constant every day for every year with its mean temperature and mean precipitation the same as that of a Temperate Forest, the organisms that would thrive there would be much different. CESs enable the thorough study of such effects. This is of particular interest as scientists attempt to predict the potential impact of climate change and enable life beyond Earth among other things.

Each biome on Earth can be viewed as loosely-connected PCESs. Mountains and bodies of water may mark natural boundaries between terrestrial biomes, but organisms and resources can pass between these biomes. The temperature and precipitation levels associated with each biome define its effective region.

Organisms not native to a biome may move to or be transported to a foreign biome, but they tend not to thrive as well as the native organisms and tend to be eliminated. When the foreign organisms do thrive, they are considered invasive species because the biome’s dynamic equilibrium changes and one or more native species tend to be eliminated. CESs can be used to more effectively and proactively study such impacts on biomes.

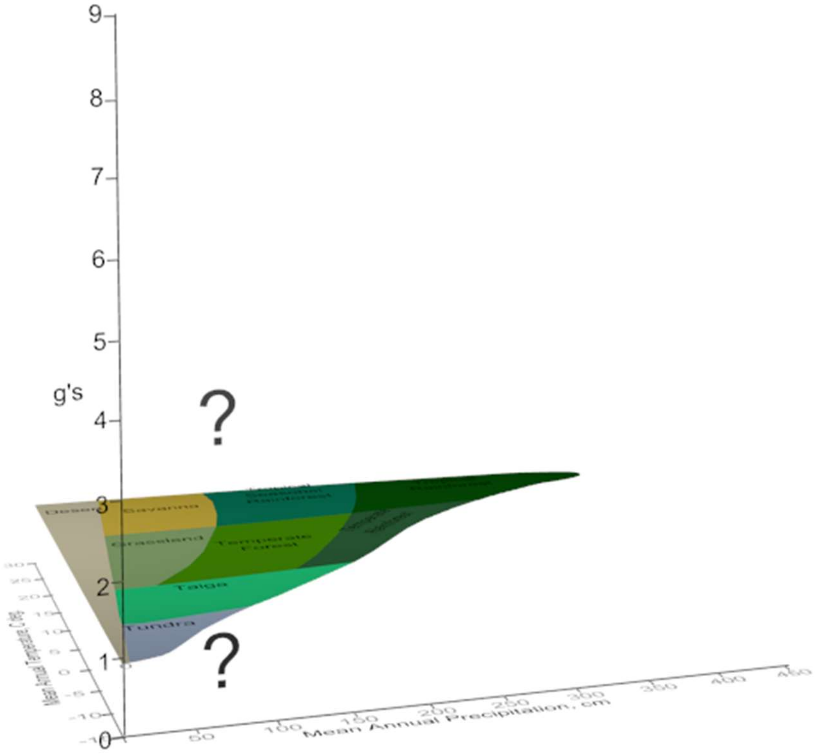


Figure 5: 3D Whittaker Biome Diagram with gravity z-axis added

Very little is known regarding the long-term (multi-generational) effects of gravity levels either above or below 1g on all known life and their biomes, as depicted for terrestrial biomes in figure 5, in which the Earth’s biomes are shown as a thin skin at the 1g level on the vertical axis. "An Artificial-Gravity Space-Settlement Ground-Analogue Design Concept" (Dorais, 2016) describes a concept that would enable a network of human-occupied PCESs subject to gravity levels above 1g to be operated on Earth. However, fractional gravity under 1g can only be generated for a few seconds on Earth, essentially by powered descent. This paper describes a spacecraft design concept to orbit CESs that are subject to various gravity levels, both above and below 1g for long-term study.

Microbiomes

For about the first 3 billion years, the life on Earth appears to have been microbial with multicellular life not appearing until about 600 million years ago. To this day, microbes are essential for multicellular plants and animals. On average, humans have on the order of 10 times the number of microbes on and in their bodies than the number of their own cells. Most of these microbes are either benign or helpful, such as by aiding digestion, recycling organic materials, building up our immune systems, and protecting us from the small percentage of harmful microbe species.

Microbial biomes (microbiomes) are extremely complex and their impact on engineered environments is an active area of research (National Academies of Sciences, 2017). A single liter of water or earth may contain billions of microbes of a wide variety of species that are continually changing in quantity, evolving genetically, and interacting with each other as they compete for resources. Microbiomes exist within organisms, such as human intestines, aquatic environments, such as ponds and oceans, terrestrial environments, such as top soil, and engineered environments, such as buildings and CESs. Each microbiome requires some combination of fresh water and salt water as a base. Microbiomes can be extracted from their natural environments as well as be created in the lab by combining microbes and resources.

Since microbes play a critical role for all life, they play a foundational role in the development of the CESs for the CCEDS. Due to the complexity of the microbes in the environment as well as in each plant and animal, the CCEDS does not model the individual microbes or even most of the microbe species. However, the CCEDS does model classes of microbe species, such as phytoplankton, which convert light to chemical energy, and select individual species that can be used as measures of the health of a microbial CES.

Each CCEDS CES is a colony of CES Modules (CESM). Once a microbiome is created, it is sealed and treated as a CESM. The CCEDS methodology under development for creating microbial CESMs includes extracting microbiota from a natural site, creating CESMs per recipes written by experts, evolving recipes by the CCEDS from a population of recipes, merging two or more CESMs, or a combination of these methods. The CESM is controlled such that the microbiome reaches equilibrium for a range of temperatures and lighting time-series. If microbes cannot survive under the CESM environment conditions, it is less likely that multicellular plants and animals can.

Once a microbial CESM reaches equilibrium and is deemed suitable for use in a CES with multicellular plants and animals, the microbiome CESM is selected for propagation. For an aquatic CESM, this is accomplished by creating one or more sterile CESMs with filtered water, filtered air, and filtered carbon dioxide, from commercial tanks or dry ice, which sublimates. These ingredients provide the necessary elements for life: hydrogen, oxygen, carbon, and nitrogen, as well as other trace elements in the air and water. Other materials can also be added, including non-reactive materials such as synthetic gravel, to provide a healthier environment for the various microbes to live. One or more of the sterile CESMs are then connected to the microbial CESM selected for propagation. Pumps are used to mix the waters so that each connected CESM has approximately the same amount of water with the same microbe populations. Once this connected network of CESMs reaches equilibrium, they are marked as part of the same lot and then separated. The process can be repeated as needed.

Essentially, each CES microbiome lot is treated as the same species. They reproduce as described above, but they can also create new microbiome lots by combining microbiome CESMs from two or more different lots. The ancestry of each of these microbiome CESMs is tracked like one would track the breeding of animals, such as horses or dogs, with the exception that a microbiome can have any number of parents.

Microbial terrestrial CESM preparation is similar to the preparation procedure for fresh-water aquatic CESMs with the following exceptions:

- The initial microbial population sample it consists of is based on soil instead of water, but water is added.
- Sterile terrestrial CESMs include sands and powered carbon in addition to the ingredients for sterile aquatic CESMs. Note that the total carbon mass in a CESM limits the maximum biomass in the CESM (unless it is connected to another CESM).
- In order to connect a sterile terrestrial CESM with a microbial terrestrial CESM such that the microbe populations are uniformly distributed, the soils in the CESMs must be mixed. A uniform distribution is not required, but then the performance of each CESM may vary considerably. Mixing can be accomplished by placing the soils from all the CESMs into a tumbler where they are mixed like a cement-mixer mixes cement. The liquefied soil can then be pumped back into the CESMs like cement can be pumped for construction purposes. Another alternative for mixing soils is the use of underground augers running the length of the CESMs to ports connecting the CESMs. By rotating the augers, soil is mixed and moved from one CESM to the next. Augur-equipped CESMs do not mix the soils as effectively as the tumbler approach, but they can be used over the operational life of the CESMs. Plants and animals can also be used to redistribute soil between CESMs as needed.

As with the microbial aquatic CESMs, once the connected microbial terrestrial CESMs reach equilibrium, they are marked as part of the same lot and then separated.

Once a microbial CESM reaches equilibrium, multicellular plants and/or animals can be introduced to it via a CESM port. Doing so will generally disturb the CESM equilibrium depending on the size of the CESM and the specimens added. Once the specimens are added, it may be necessary to connect the CESM (with one or more other CESMs in order to reach a new equilibrium. For example, one CESM with animals may produce excess carbon dioxide and require additional oxygen while another CESM with plants may produce excess oxygen and benefit from additional carbon dioxide. Microbial CESMs without multicellular plants and animals can also reach new equilibria where they effectively convert carbon dioxide to oxygen, or convert oxygen to carbon dioxide, for other CESMs.

Aging and Evolution – Aging is a familiar characteristic of multicellular plants and animals. A 1-year old tree, a 10-year old tree, and a 100-year old tree are clearly distinguishable. The same holds for humans. In addition, plants and animals have well-defined life spans. They essentially are designed to die such that it would be an incredible surprise if such an organism did not age. The same does not hold true for a microbiome in a CESM, which can be considered as a single multicellular, multi-genome organism. Once the microbiome reaches equilibrium and its environmental temperature, radiation, and gravity levels do not stray from their established norms, the organism does not appear to age. We hypothesize that a 1-year old CES microbiome, a 10-year old CES microbiome, and a 100-year old microbiome may be completely indistinguishable by experts. Rather, it appears as if they could live indefinitely. As is the case for multicellular plants and animals, microbial cells reproduce and die. However, a resource-producing organism that the microbiome comprises may be able to continually produce oxygen, or carbon dioxide, or food among other things indefinitely. The above hypothesis depends on gravity being held at 1g.

Establishing microbiome equilibrium at a different gravity level may be possible and may result in microbe populations evolving in the process, but could take considerable time to confirm given the 4 billion years of microbial evolution at 1g. The evolutionary paths that microbiomes follow at fractional gravity levels may be predicable given sufficient time and quantity of CES samples subject to fractional gravity. This could have consequences for all life subject to fractional gravity for extended periods.

Astrobiology

Astrobiology is defined by the National Academies of Sciences, Engineering, and Medicine (NASEM) as, "the study of the origin, evolution, distribution, and future of life in the universe." (NASEM, 2018). Congress directed NASA and NASEM to develop an astrobiology science strategy, which is defined in (NASEM, 2018). This document describes a rapidly growing field and has several recommendations. The primary focus of the document appears to be on the search for extraterrestrial life as opposed to the study of life beyond Earth that originated on Earth. After 60 years of space travel, almost nothing is known about populations of organisms that are conceived and mature in space by competing for their survival and reproduction thereby evolving in space over multiple generations. The CCEDS develops CESs that are suitable for long-term spacecraft payloads to facilitate the study of the evolution, distribution, and future of life in the universe beyond Earth from life that descended from life on Earth.

Controlled Ecological Life Support Systems (CELSSs)

In addition to improving the scientific understanding of organisms and their communities, CESs show promise as a means of life support for humans in space. NASA began a sustained effort to develop CELSSs in 1978 with the start of the CELSS Program to develop technologies to sustain sizable flight crews in space for extended periods by means of fully-integrated bioregenerative life support systems, which include biological and physico-chemical subsystems for recycling resources. These subsystems included:

- "Biomass production (plant and secondary animal production)
- Biomass processing (food production from biomass)
- Water purification
- Air revitalization
- Solid waste processing
- System monitoring and control" (Averner, 1990).

The CELSS Program funded a wide variety of activities including those focusing on CESs. Several of these activities were discussed at the CELSS workshop, "Workshop on Closed System Ecology" at which CES research was presented (NASA CR-169280, 1982). The unanimous findings of the workshop participants were:

- "It may be much easier to achieve persistent materially closed ecosystems than had been believed in the past.
- CES research promises to become a significant resource for the resolution of global ecology problems which have thus far been experimentally inaccessible because:
    - Global parameters (e.g., O_2 or CO_2) of whole ecosystems can be monitored under controlled replicable conditions.
    - Boundary conditions such as chemical, biological, and physical starting values and post closure energy fluxes can be varied experimentally.
    - Global energetics of whole ecosystems can be measured and experimentally manipulated.
- For the reasons just cited, closed ecology research may very well prove an invaluable resource for predicting the probable ecological consequences of anthropogenic materials on regional ecosystems.
- CES research is an empirical resource for validating and calibrating general and special mathematical models of ecosystem structure dynamics and stability characteristics.

- CES research may become pivotal in discovering the basics laws to which Controlled Ecology Life Support Systems (CELSS) must conform and in establishing the foundation for a CELSS control theory." (NASA CR-169280, p.2).

Subsequently, the growing concern regarding climate change and the increasing rate of species going extinct make the above findings even more prescient. These findings continue to be relevant for CES research and support the need for systems such as the CCEDS.

Among the CES activities discussed at the workshop was a 1-liter CES containing microbes, algae, and Crustacea developed by J. Hanson that had persisted for nearly 2 years by that time (NASA CR-169280, p.9). The following year NASA licensed the technology for this CES to a company that commercialized the product and began marketing ecosystems in 1983. To date, nearly 1 million of these CESs have been produced since then (EcoSphere History, 2018). An example of one of these CESs is shown in figure 6.

Figure 6: 6.5" diameter EcoSphere

Courtesy of Ecosphere Associates, Inc., Tucson, AZ, USA

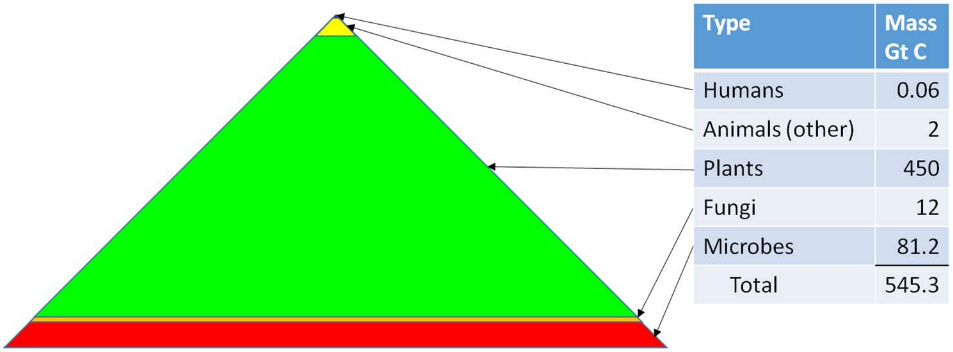
With the exception of nine Apollo missions, in the last 60 years of spaceflight all human-occupied spacecraft have not gone beyond low Earth orbit and only a few astronauts have continuously stayed in space more than 7 months. For these reasons among others, there has been little investment and little progress in CES research since NASA's promising start 35 years ago. Currently, it is simply less expensive to regularly ship supplies to flight crews than recycle resources. For the same reason, flight crews discard their clothing rather than washing them. However, this approach is short-sighted given NASA's goal is to extend human presence throughout the solar system.

Once CESs are demonstrated to reliably persist in space, within specified gravity and radiation limits, it is a small step for similar CESs to persist just about anywhere in space (Earth orbit, Moon, Mars, Earth-Mars cycler orbits, asteroids, …) enabling life to permanently extend beyond Earth and grow exponentially. In 1986, Dr. Carl Sagan authored a magazine article titled, "The World that Came in the Mail" about a 5" diameter EcoSphere closed ecosystem, in which he stated, *"Such systems are being perfected and will play a key role in future human exploration of the solar system."* (Sagan, 1986), and in which he described a EcoSphere similar to the one shown in figure 6 that he received (EcoSphere Carl Sagan Review, 2018). C. Sagan subsequently authored *A Pale Blue Dot: A Vision for the Human Future in Space* (1994) where he made a case for permanently extending life beyond Earth.

However, due to the complexity of CESs, they tend to be unpredictable and difficult to control, particularly those with animals, e.g., the largest animal species tend to go extinct first because the largest animals tend to have the large resource demands and low populations with respect to the other species in the CES they rely on, which would be the case for CESs and/or PCESs with humans. This challenge is the motivation for developing the CCEDS.

A Bioregenerative Life Support System Primary Challenge

Bioregenerative Life Support Systems present a number of challenges. However, the Earth's biosphere itself demonstrates the feasibility of such systems. It has functioned for about 4 billion years while subject to a wide range of destructive events, both geological and astrophysical. A primary reason for this resilience is suggested by figure 7.



Type	Mass Gt C
Humans	0.06
Animals (other)	2
Plants	450
Fungi	12
Microbes	81.2
Total	545.3

Figure 7: Current Total Biomass Carbon Estimate by Type

Since the water within an organism can vary considerably, total carbon mass is commonly used as a biomass metric. A recent study of the Earth's total biomass distribution by type (Bar-On, Phillips, and Milo, 2018) is summarized in figure 7 by the table listing Gigatonnes of Carbon (Gt C) distributed by biomass type, which is graphically depicted by the layered triangle shown in the figure. The study does characterize the uncertainty of the estimates, which is highest for the microbes and lowest for humans. The majority of the plant biomass is due to tree species.

With respect to bioregenerative life support for humans, on Earth the order-of-magnitude ratio of human biomass to non-human biomass is currently 1:10,000, i.e., (0.06/(545.3-0.06)). However, due to the recent growth of the human population and deforestation, the general consensus is that the Earth's ecosystem would be more sustainable with fewer humans and more trees pushing this ratio much higher, e.g., 1:100,000.

In contrast to the natural ratio of humans to other life, humans continue to migrate to cities at an accelerating rate, where the human biomass is orders of magnitude greater than the non-human biomass. Consequently, cities require a constant inflow of food, water, air, and other resources, and produce a constant outflow of wastes to a point damaging Earth's biosphere.

For humans in space, this extreme is pushed even further. On the International Space Station, a regular stream of supply spacecraft is required to sustain the lives of the crew. Most of these supply spacecraft are subsequently filled with wastes to be incinerated in the Earth's atmosphere. Other wastes, such as methane, are exhausted into space. This process is even less attractive for when humans live on the Moon, Mars, and beyond where bringing wastes back to Earth for disposal is not an option. The technologies that will enable humans to live sustainably in space will almost certainly be applicable to the cities on Earth benefitting all life.

The preliminary findings of CES research indicate that animal to plant biomass ratios much closer to 1:10 are achievable, at least for a few years as demonstrated by the success of EcoSpheres (figure 6). CCEDSs can be used to explore the feasibility of different ratios for different combinations of species populations, eventually including humans.

Controlled Closed-Ecosystem Development System (CCEDS) Design Concept

The CCEDS design consists of a network of independent CESs, each consisting of a colony of CESMs equipped with sensors, actuators, controllers, and communication equipment (see figure 8 and tables 1-3). These CESMs are combined into independent CESs that are governed by a CCEDS that uses the CESs to generate data to continually optimize the overall system.

Controlled CES Modules (CESMs) Equipped for Data Collection and Optimization

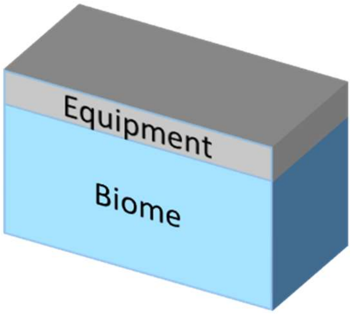


Figure 8: A Controlled CESM Example

Table 1: CES Candidate Sensors

Sensor
Temperature Sensors
Microscopes
Imagers, variable frame rates
Multi-spectral Light Sensors
Pressure Sensors
6-axis Accelerometers
GPS/location Sensors
pH Sensors
Humidity Sensors
Spectrometers
Genomic Sensors
Magnetometers
Radiation Detectors

Table 2: CES Candidate Actuators

Actuator
Multispectral Lighting
Heaters/ Coolers
Humidifiers/Evaporators
Dehumidifiers/Brine Collectors
Precipitation Mechanisms, e.g., Misters

Actuator
Water pumps & valves
Air pumps & valves
Organism gates
Fans
Robotic arms
Sampling Mechanisms
Electromagnets
Lasers
Vibrators
Augers

Table 3: CES Other Candidate Components

Component
CPUs
Memory Storage
USB Ports
Actuator Controllers
Analog/Digital Converters
Internet Controllers
Power Supplies

The above lists itemize components under consideration and not intended to be exhaustive.

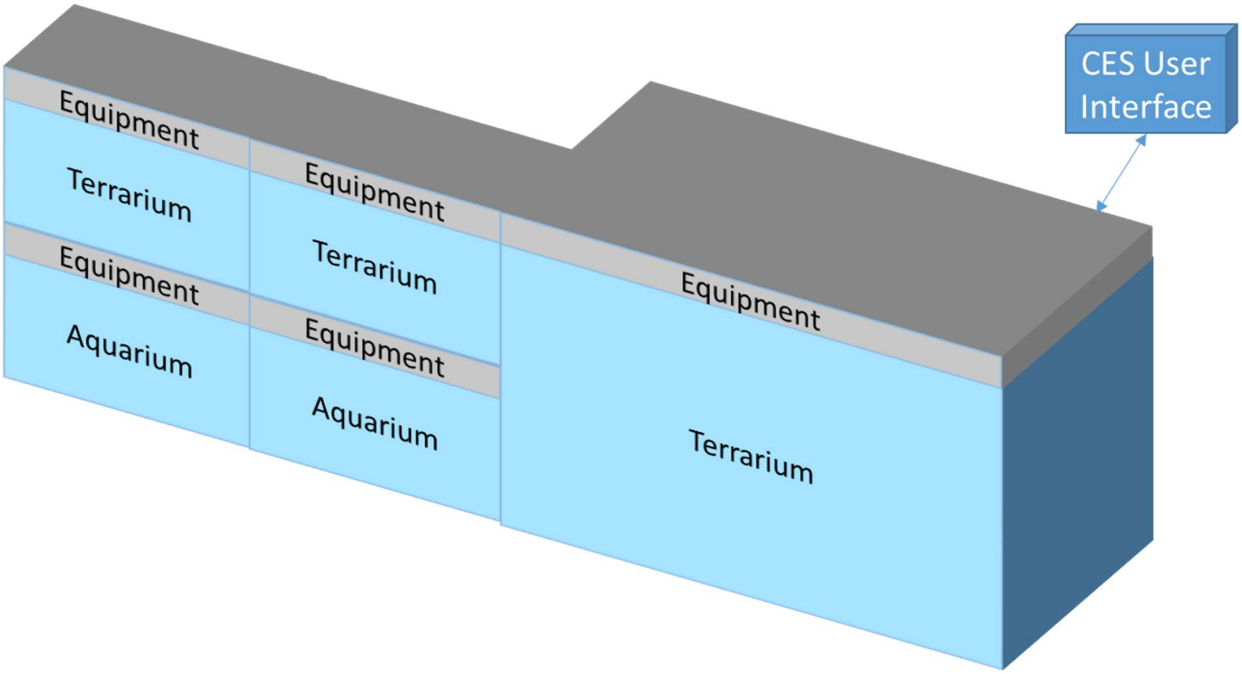


Figure 9: A Controlled CESM Colony Example

As depicted in figure 9, the colony of CESMs that comprise a CES can be attached together in a wide variety of configurations to increase the organism variety, size, population, capacity, and sustainability of the CES. The transfer of gas, water, and organisms between CESMs can be controlled (e.g., some CESMs may be designed to produce excess oxygen and others to produce excess carbon dioxide).

CES Module (CESM) Types

Each individual CESM can be configured in a wide variety of ways and can be reconfigured during operation, both mechanically as well as naturally to facilitate inter-CESM resource flows. For design and analysis purposes, it is helpful for humans to classify CESMs by different quad-types, one type from each of the six classes: Environment, Biota, Climate-Temperature, Climate-Precipitation, Gravity, and Production. The CCEDS is free to blur these distinctions and morph the CESMs as needed.

For example, figure 9 depicts a CES comprised of 2 aquarium CESMs and 3 terrarium CESMs. If for some reason, most of the water from one aquarium was pumped into the other CESMs, the same CES would then be comprised of 1 aquarium and 4 terrariums. Each of these CESMs may have a different climate, support a different set of species, and perform a different function in the CES by contributing different resources that benefit the other CESMs.

The following CESM types appear to be useful building blocks and are offered as examples, but the system is expected to evolve a much wider portfolio to draw from over time:

Environment (General) Types

Aquarium – The CESM water surface area is significantly greater than the land surface area. There may be no land surface area. Water provides additional protection from radiation and rapid thermal changes for space CESs. The salt content can vary from fresh water to sea water.

Terrarium – The CESM land surface area is significantly greater than the water surface area. There may be no water surface area. This CESM generally requires more volume for an atmosphere than an aquarium CESM to support larger land animals and plants.

Coastal (Aquarium/Terrarium bridge) – The CESM land surface area and water surface area are similar in size. This CESM type can act as a bridge between an aquarium CESM on one side and a terrarium CESM on another side.

Subterranean – This is a variation of a terrarium CESM in which there is no water surface area and most of the volume consists of soil for harboring underground biota. The soil provides additional protection from radiation and rapid thermal changes for space CESs.

Biota (Prominent) Types

Microbiome – As described in the Microbiome section above, microbes play a critical role in all CESs. Microbes will persist in all viable CESMs, but having a persistent source of microbes as well as the resources they can provide, e.g., oxygen, makes it an important CESM type.

Botanical Garden – Plants account for the vast majority of all the biomass on Earth playing key roles for the nutrition and oxygen for animals, both terrestrial and aquatic. This CESM type also includes support animals, such as worms, snails, and other Spiralia.

Insectarium – Insects may not be essential for some CESM colonies, but they do play important roles in Earth's ecosystem, such as pollination and as a nutrition source. Candidate species include bees and ants. Although technically not insects, this CESM type may benefit by including arachnids.

Amphibian Zoo – Amphibians are an optional set of species, but may play an important role in controlling insect populations and as a nutrition source for other species.

Reptilian Zoo – Reptiles are also optional for many CESM colonies, but may play an important role in controlling a wide range of species populations, including mammals.

Aviary – Aviaries are optional for CESM colonies. Birds can be both aquatic and terrestrial foragers as well as effective at spreading and fertilizing seeds. A bird can also literally act as "the canary in a coal mine" sensing the suitability of the atmosphere for sustaining life. Little is known about bird flight under different gravity conditions.

Aquatic Biota – Rather than segmenting the aquatic biota into subcategories, they are grouped together in this type to support a wide variety of plant and animal combinations. Separate CESMs may be useful to support incubation and maintain diversity.

Mammalian Zoo – This CESM type focuses on supporting mammal populations of increasing size to eventually demonstrate that human populations can sustainably thrive in CESMs since this is the ultimate goal of this effort. However, initially the plan is to start with rodents, weasels, and other small mammal populations that look promising for persistent CESs.

Climate-Temperature Types

Arctic – CESMs with annual temperature ranges that fluctuate above and below 0°C such that surface ice forms and melts, but does not get so thick it jeopardizes the CESM's biota. Many organisms important to Earth's ecosystem, such as phytoplankton and krill, thrive in colder temperatures.

Temperate – CESMs with moderate daily and seasonal temperature ranges that fluctuate above and below 20°C. This temperature range supports a wide variety of Earth's biota.

Tropical – CESMs with daily temperature ranges that fluctuate above and below 30°C. This temperature range is conducive for biota not suitable for cooler temperatures.

Climate-Precipitation Types

Dry – CESMs with an annual precipitation between 0-50cm. Additional water can be provided by a subsurface source and an oasis can support life in lieu of precipitation. CESMs with high concentration of animals may thrive better in a dry climate as long as a water source is available. This type of CESM may also be suitable for evaporating brines and salt storage.

Moderate – CESMs with an annual precipitation between 50-175cm. The distribution of this precipitation can vary seasonally to encourage plant growth.

Heavy – CESMs with an annual precipitation between 175-400cm, primarily for supporting tropical biota.

Gravity Types

CESMs can be subject to a spectrum of gravity levels that remain constant or that may continuously change. On Earth, the CESMs are limited to Earth and Hyper gravity levels. In space, Micro, Lunar, and Martian gravity levels are of particular interest due to their proximity and potential to harbor life.

Micro – CESMs subject to acceleration near 0 m/s^2; a gravity level suitable for simulating spacecraft cruise flight conditions, such as present on the International Space Station.

Lunar – CESMs subject to acceleration near 1.6 m/s^2; a gravity level suitable for simulating Lunar near-surface conditions.

Martian – CESMs subject to acceleration near 3.7 m/s^2; a gravity level suitable for simulating near-surface conditions on Mars.

Earth – CESMs subject to acceleration near 9.8 m/s^2; a gravity level suitable for simulating near-surface conditions on Earth. This is the baseline gravity type for CESMs.

Hyper – CESMs subject to acceleration above 9.8 m/s^2; a gravity level suitable for simulating a gravity-level differential on Earth by means of centripetal acceleration. The effects of rotating CESMs can be tested on Earth before testing them in space. Also, similar CESMs can be subject to long-term tests at different gravity levels including enabling organisms to travel between CESMs subject to different gravity levels. Different organisms within a species and different species may thrive in hypergravity environments for a variety of reasons. Hypergravity simulator benefits and design consideration are discussed in (Dorais, 2016).

Production Types

Oxygen producer – CESMs that produce excess oxygen in exchange for carbon dioxide.

Carbon dioxide producer – CESMs that produce excess carbon dioxide in exchange for oxygen.

Vegetation producer – CESMs that provide plant nutrition for animals.

Meat producer – CESMs that provide meat nutrition for animals. In the long term for the Darwinian evolutionary selection process to function, animal populations must be culled based on their fitness with respect to their environment. This is particularly important for a species population to adapt to a foreign environment, such as those in space.

Fertilizer producer – CESMs that provide nutrition for plants. The primary source is microbes and the waste they feed on.

Pollinator producer – CESMs that enable plants to pollinate and disburse seeds. Naturally, this is done by wind and some animals. However, a CES could be equipped to perform this task mechanically.

Mineral producer – CESMs that provide mineral nutrition for biota. By definition, all CESs are closed so the total mineral content is fixed. However, over time the minerals may become distributed in a way that hinders growth in some CESMs such that mineral redistribution is required. This can be accomplished by strategically controlling water flow as well as by animals and mechanical means.

Universal producer – CESMs may serve different functions for the CES depending on what is needed at any particular time. A universal-producer may be tuned by the CCEDS to produce oxygen when needed; and then be re-tuned to produce carbon dioxide to prevent the oxygen level in other CESMs from becoming too high. Because of their flexibility, universal producers can be independent from other CESMs. One strategy a CCEDS may employ is to keep universal producers disconnected from the other CESMs unless they are needed in order to protect the flexible capability and diversity of their role as universal producers. Otherwise, the CESMs may specialize over time and lose their flexibility as universal producers.

These CESM building blocks can be combined in a variety of ways during the CES design process as well as dynamically reconnected and individually retuned during operation as directed by the CCEDS operating in conjunction with human experts. This operation can be extremely complex to perform effectively. The CCEDS relies on evolutionary computation to manage and optimize its continually adapting CESs.

CCEDS Architecture

Figure 10 depicts the CCEDS Architecture.

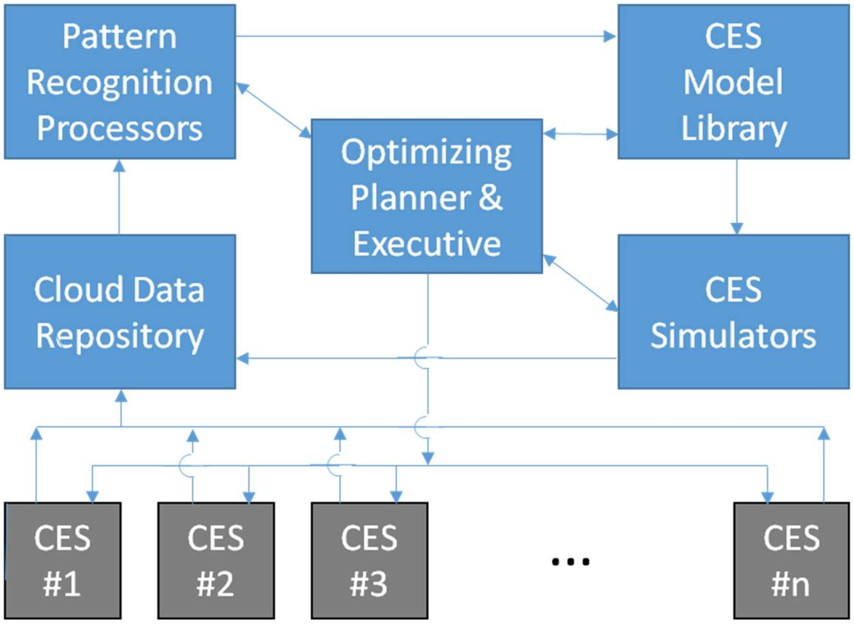


Figure 10: CCEDS Architecture Overview

The architecture consists of the following five CCEDS control system elements in addition to its population of CESs that generate data for and execute commands from the CCEDS control system. Together with optional inputs from human experts they form an adjustably-autonomous, self-optimizing network for closed ecosystems in which data collected from each physical CES and the CES simulators are used to optimize the individual CESs and the CES Model Library Artifacts. The following five CCEDS control system elements are briefly described below. The architecture simultaneously supports one or more independent CESs, each comprised of one or more CESMs that can be dynamically interconnected within the CES by command.

Pattern Recognition Processors (PRPs)

The PRPs detect patterns in the data from the CESMs as well as the CCEDS control system elements. Because of the large amount of time-series data a population of CESs can continually generate, including images, and the complexity of the patterns hidden in this data, which continually change over time, the computational resources required to maximize the potential of the PRPs in discovering useful patterns are not bound. This element of the architecture can function with a single processor, but the design is computationally distributed so that it can take advantage of whatever level of computational resources are available. In addition to CPUs and GPUs, cloud computing and specialized processors such as Tensor Processing Units (Jouppi et al., 2017), analog processors, and neuromorphic processors are being considered as candidate processors.

Optimizing Planner and Executive (OPE)

The OPE uses patterns discovered by the PRPs to optimize the CESs and the CCEDS control system elements. The OPE can either operate in a command mode or advisory mode for each CES. In command mode, the OPE issues commands to each CESM based on its overall analysis of the CESs in order to optimize the value of the data generated by the CESs, maximizes the persistence of CES organisms, and/or other system-level objectives. In advisory mode, the OPE issues status reports, advisories, and CESM controller command sequence change recommendations to the CES user interface. It is left to human experts/users to determine which command changes are warranted and executed by its CESMs. In both modes the CCEDS issues software updates to the CESM controllers and CES user interface.

Cloud Data Repository (CDR)

The CDR stores sensor data and command logs received from the CESMs and the CES simulators. The CDR also services data access requests by the PRPs and CES simulators.

CES Model Library

This element is a repository for artifacts used by and/or optimized by the OPE and PRPs as well as human experts. These artifact types are listed in table 5.

Table 5: CES Model Library Artifacts

Library Artifact
Organism Models
Environment Models
CES and CESM Recipes
Resource Recipes
Inter-CESM Configurations
Intra-CESM Configurations
Control Algorithms
Heuristics
Simulation Scenarios
Simulation Histories
CES and CESM Predictions

CES Simulators

The CES Simulators can run much faster and simulate many more variations of simulated CES systems by a few orders of magnitude than the physical CESs, which are used to validate the simulations. A CES simulator can run at a variety of fidelity levels selected as needed. High fidelity simulations require more computational resources and take longer to simulate a period of time, which can be very long, such as for the case when the simulation exit criterion is that the CES becomes sterile. Low fidelity simulations run faster, but with the disadvantage that the results tend to be less reliable. In many cases, it is more valuable to quickly have many rough estimates than to have a few very accurate estimates. In other cases, such as when diagnosing an unexpected result, accurate estimates are more valuable and worth the wait.

Evolutionary Computation

Evolutionary computation (EC) is the area of computer science that encompasses stochastic design and optimization algorithms based on rules derived from evolutionary theory and genetics. EC is often suitable for solving problems not amenable to traditional approaches as well as to better understand not only nature, but complex adaptive systems in general. CESs are such systems.

The essence of EC algorithms is described by the following 5-step process:

1. A limited population of candidate models is generated
2. The population is reproduced with deviations
3. The fitness of each member of the population is determined
4. The least desirable members are either removed or made less likely to reproduce
5. Return to step 2 until the exit criteria are met

The EC algorithms being designed for the CCEDS are based on EC algorithms described in (Dorais, 1997). For this system, the EC algorithms themselves are in the process of being modeled and evolved recursively by EC algorithms in order to optimize the wide range of parameters EC algorithms use for a particular domain, in this case CESs. The model representations of the physical ecosystems are also in the process of being evolved by EC algorithms to determine the best model representation. A model that is too simple or too complex will not effectively predict the life cycle of a CES under various conditions.

CCEDS Evolutionary Computation Step Details

The 5-step EC algorithm specified above summarizes the process, but the details are tailored for the application and can be very complex in order to be effective. The following describes each step in more detail as it applies to the CCEDS application.

Step 1: A limited population of candidate models is generated.

This step entails three significant design considerations: the model population limits, the model representation schema of the population elements, and the initial model generation process.

The model population limits are dependent on the size of the model search space and its complexity. If the limits are too small, then the algorithm will prematurely converge on a local optimum, overlooking better solutions. If the population is too large, it can slow the optimization process. If the population size exceeds the search space, the algorithm simply becomes an exhaustive search where the optimal solutions are in the initial population. For this application, the possible solutions are effectively infinite so exhaustive search is not an option. The enormous size of the search space is due to the number of parameters used to define each model, the number of values each parameter can take, and several other factors. The CCEDS process grows the number of model parameters and their ranges so the search space increases over time. This is not as problematic as it may seem because life does not have to be optimal to survive, but it helps increase the odds that CESs will persist if their models continually improve.

For this application, the limited model population is divided into a number of subpopulations, each with their own limits. This is done to help the algorithm to more thoroughly explore the search place rather than focus on the simplest, most promising solutions.

The model representation schema for CES can be extremely complex so finding the model complexity balance is continually being tuned as part of the algorithm optimization process. Nature encodes the model of each organism in DNA. Given the DNA, nature can reproduce the organism. However, how nature does this for a single organism is still beyond the capability for computers to simulate. A CES is comprised of one or more CESMs, with CESMs being added to and removed from the CES over its operational life. Each CESM can be controlled over time differently, be a different size, be connected to other CESMs differently, and contain billions of microbes that widely vary genotypically and phenotypically, the vast majority of which can be unknown to science. The CESM schemas used are extreme simplifications, but are designed to be sufficiently complex to improve the likelihood of CESs persisting.

The initial population of models can be randomly generated, where each model parameter is randomly selected from its range of values. This would distribute the possible solutions across the search space, but would not be productive. Most of the solutions would not be helpful in that they would either define a CES that clearly would not be viable as determined by an expert or would not be meaningfully different, which would waste computation time. Initially, the population is seeded with models from experts for CESs that are known to be viable and/or help direct the search as well as models extrapolated between expert-specified models. This is part of the adjustably autonomous aspect of the CCEDS algorithm. It can benefit from the advice of experts while still exploring options that experts have not considered.

Step 2: The population is reproduced with deviations.

This step uses variations of genetic algorithms. Nature either uses asexual or sexual production to produce organisms with DNA that are similar, but different from the parent organisms. In asexual reproduction, a cell divides with attempt to duplicate the DNA, but errors can occur, which are called mutations. The mutation rate is highly dependent on the radiation the organism has been subject to prior to and during the reproduction process. The CCEDS genetic algorithms use a tunable mutation rate to enhance the search space depending on the complexity of the local regions of the space being explored.

It turns out that sexual reproduction is a far more effective mechanism for exploring complex, dynamic search spaces. Keep in mind that in a CES, as on the Earth, the search space is continually changing. Organism populations that once thrived may no longer do so because the environment including other species have changed. Sexual reproduction introduces the concept of DNA chromosome crossover where the DNA of the species is divided into multiple chromosomes and is combined in a way that the offspring receive DNA from both parents, both of which have had to survive long enough in the current and prior environments in order to reproduce, thus demonstrating their fitness, filtering out DNA that is currently less effective. It is incredibly amazing that this crossover process actually works. It is similar to taking multipage blueprints for two different computers, randomly tearing each page into multiple pieces, mixing the pieces for each page for both computers together, randomly selecting the pieces for each page, attaching them together, manufacturing a new computer according to this new blueprint, and the new computer almost always works! The CCEDS algorithm uses crossover to combine the design of two or more models in the population in addition to mutation to generate the next generation with deviations. Unlike nature, but similar to genetic engineering, this algorithm does not restrict organisms from having more than two parents.

Step 3: The fitness of each member of the population is determined.

This is the most challenging step and is continually tuned as part of the algorithm optimization process. It involves essentially analyzing the model parameters of each model in the model population and deciding how a CES built and controlled according to these parameters will persist over time compared to the other models. Even an expert looking at multiple physical CESs will have trouble determining which CESs are more likely to persist longer. It is not even clear what is being optimized, i.e., how is fitness defined? In nature, fitness is associated with both organisms and species. Stochastically, the more fit organisms reproduce and the more fit species persist. Fitness is not necessarily a function of size, strength, intelligence, beauty, or dexterity. However, it is a function of adaptability, which depends on a wide variety of attributes. The fitness function of the CESs focuses on the species and classes of species instead of the individuals, but this simplification is only the first step in the fitness function optimization process currently underway.

It may first appear that the problem of defining a CES fitness function is simple. If the CES contains living organisms, the function value is 1, otherwise it is 0. However, such a fitness function is not very helpful in guiding the search process. Its one redeeming value is that once everything is dead in a CES, nothing will spontaneously generate so the CES can be repurposed. Also note that the fitness function of a model is different than the fitness function of a physical CES where sensors measure the CES state. In addition, a binary fitness function does not capture the uncertainty of the assessment. The probability of false positives and false negatives are not captured. Also, this binary fitness function is not predictive and does not guide the search process by enabling the ranking of the physical CESs as well as the CES models in the CCEDS algorithms population.

So instead of a binary fitness function, consider a numeric measure such as biomass kg, e.g., the higher the biomass, the more fit the CES. This has several problems as well. With EC systems one needs to be careful for what is ranked highly, you might just get it. It may turn out that the highest biomass is achieved by killing all the plants and animals so that their carbon can be used for microbes.

Given that the long-term goal of this effort is to sustain human life in CESs or PCESs, couldn’t mammal count be an effective fitness measure such that the greater the quantity of mammals in a CES is, the more fit the CES is? This metric also has several problems. Consider a CES that supports a population of mice and the CCEDS is trying to maximize the count. One outcome is that so many mice are born that all the food and oxygen are consumed and they all die. Let’s say that the CCEDS predicts this outcome and provides the needed food and oxygen; then the mice reproduce until it becomes so crowded that the female mice stop reproducing. Once the youngest female mouse reaches menopause, the CES is doomed. The mammal count remains high for a while, but one by one they die of old age until the species is extinct.

The mammal count is an important part of the fitness of a CES, but it is more complicated than simply the maximizing the count. Recognizing the mammal population requirements, e.g., food, and the negative environmental effects it produces, e.g., wastes, are considered key to an effective CES fitness function that stochastically predicts mammalian sustainability. Also key to an effective fitness function is accurately predicting the CES’s ability to maintain the cycle balances and the CES adaptability that the mammal population depends on.

The fitness function can be simply calculated as described above, or be learned by a deep neural network, but the current fitness function design methodology focuses on using simulators that use deep neural networks as well as other algorithms to assess fitness according to a method that is continually optimized using both machine learning and expert knowledge.

Step 4: The least desirable members are either removed or made less likely to reproduce.

The step applies the Darwinian concept of the “survival of the fittest.” Simply applied, the population is sorted by fitness and only those models above a certain cut point are permitted to reproduce. However, this approach can lead to premature optimization on a local minimum.

Another simple, but generally more effective method is to stochastically select which models reproduce with the probability of being selected based on each model's fitness. This method is also too simplistic for CESs for the same reason.

Because ecological environments are dynamic and cyclic, this step must be applied with caution. For example, in nature larger organisms tend to reproduce less frequently than smaller ones and there are several reasons why this strategy is effective. One of them involves the fact that large mammals take several years before reproducing. The Darwinian explanation for this is that it takes such organisms that long to mutually determine their fitness to reproduce and to select environmental conditions that will increase the probability that their progeny will also survive long enough to reproduce.

For CCEDS models, this process is accelerated by simulating the fitness of the models several years into the future under a variety of conditions. Still, these simulations are crude approximations at best even though the CCEDS process continually improves them. There is significant uncertainty in the fitness assessment for each model in the population, for several reasons including because their environments can change, either by command or due to internal CES reactions. In the CCEDS algorithm, CES models are removed stochastically based on fitness, but instead of necessarily being deleted, there is a chance that they are either transferred to a different subpopulation being evolved (similar to a major-league athlete being traded to a minor league), or stored in the CES Model Library with a chance to be resuscitated for use at a later time (cryonics analogy).

Step 5: Return to step 2 until the exit criteria are met.

Normally, for EC algorithms, this is the simplest step. For the CCEDS, one can make the case that it never stops. There is always a chance that a better model will be found. What the best model could be is not known; and even if it were found, the environments are continually changing so it would need to change too. The intent is for CCEDS algorithms to run indefinitely and in parallel on as many processors that are available. Options for crowd computing to support this effort are currently being considered.

Instead of using this step to determine if it should stop, the CCEDS uses this step to optimize the CCEDS algorithm itself including everything from fitness functions to simulations. One method the CCEDS uses to accomplish this is to apply different CCEDS algorithms (evolution strategies) to different model subpopulations. Step 1 describes that subpopulations are used to explore different regions of the model search space. In this step, subpopulations are created by duplicating existing model populations and evolving them with different evolution strategies in order to determine the fitness of the evolution strategies so that the evolution strategies are evolved by means similar to the model evolution algorithms. This process of evolving the evolution strategies can continually be applied recursively, but such efforts have not been explored for the CCEDS beyond recognizing that the option exists.

CCEDS Evolutionary Computation Levels

Based on an extension of the multi-level EC algorithm presented in (Dorais, 1997), the CCEDS performs variations of the above 5-step algorithm at the following 5 different levels of the CCEDS:

EC level 1: CESM Parametric Level

The CESM artifacts listed in table 5 contain a large number of parameters, such as counts, sizes, limits, rates, etc., which affect the development and operation of CESMs. At this level, EC is used to explore permutations of these parameters.

EC level 2: Intra-CESM Symbolic Level

The CESM artifacts listed in table 5 contain symbolic structures, such as procedures, which also affect the development and operation of CESMs. At this level, EC is used to explore permutations of these structures similar in principle to the way genes are permuted and exchanged when passed from parents to their offspring.

EC level 3: Inter-CESM Exchange Level

The CESMs can be selected and combined in a wide variety of configurations when assembling a CES and operating it. At this level, EC is used to explore permutations of the connections between the CESMs and how they are tuned to benefit their CES, such as by controlling a CESM to produce more oxygen and transfer it to another CESM.

EC level 4: Inter-CES (CESM Colony) Communication Level

Although the CCEDS controls a population of independent CESs, by detecting patterns in the data from the population of CESs it is currently managing as well as from stored data from other CESs in its CDR, the CCEDS uses EC, statistics, and other computational techniques to improve its performance in operating its current CES population as well as creating specifications for new CESs.

EC level 5: CCEDS EC Algorithm Level

The CCEDS algorithms themselves are subject to EC at this level. Consider a population of CCEDS each with a different EC algorithm, some slightly different and others significantly different, each controlling its own population of CESs. These independent CCEDSs can mutually improve each other by interacting at this level. Based on how the CESs perform for each CCEDS, the fitness of its EC algorithm is determined enabling each CCEDS to use EC to improve its CCEDS algorithm over time. Also, instead of physically requiring a population of independent CCEDSs to accomplish this, at this level a single CCEDS can create virtual variations of its EC algorithm (evolved clones), which it tests in its simulators to assess the fitness of each EC algorithm in order to use EC to evolve its EC algorithm. In addition, the CCEDS strategically uses its CESs to test these EC algorithm variations and to validate its CES simulators.

Design Strategies

The design problem can be viewed as an enormously complex, nondeterministic search problem in an n-dimensional space that continually changes unpredictably where n is effectively infinite. Each organism in each species in a CES is continually adapting to the CES environment and aging. Even microbial ecosystems in engineered environments, such as buildings and vehicles, are not well understood and pose significant health threats to humans and other species (NASEM, 2017).

In order to increase the probability of improving the viability of CESs, the CCEDS is being developed guided by the following design strategies.

1. <u>Start small</u>: Small in the size of the CES, organisms, # of CES, # of organisms, # of species of organisms, and CES volume. A small start enables rapid adaptation of the CCEDS and its processes, which facilitates rapid, low-cost progress.
2. Scale up the sizes of successful CESs by combining them with other CESs by interconnecting their CESMs.

3. Scale up the number of similar CESs and CESMs (use a batch development process to create a set of CESMs) to establish the repeatability of the control protocols used to manage the CESs during their lifecycles.
4. Vary the control protocols of some CESs to determine the effectiveness of various control protocols maintaining some CESs as the experiment control group.
5. Control the flow of resources and organisms between CESMs to maintain separate biomes and provide biological firewalls within a CES.
6. Simultaneously perform depthwise and breadthwise search for model development by using model subpopulations. Maintaining multiple model subpopulations avoids premature convergence on solutions, i.e., avoids local optima.
7. Use an adjustably autonomous approach that enables human experts to partially bias the search. By simultaneously performing breadthwise search, the EC algorithm can still discover solutions not imagined by the experts.
8. Continually optimize the optimization process using the EC algorithm.

Orbiting Fractional-Gravity Closed Ecosystems

Fractional-Gravity Closed Ecosystems

On Earth, CESs are strongly affected by the gravity generated by the mass of the Earth and are shielded from strong solar radiation and galactic cosmic rays by Earth's atmosphere and magnetic field. In order to create CESs orders of magnitude smaller than the Earth that can function without the Earth, the desired gravity level and necessary radiation shielding must be provided by other means.

CESs can be used as spacecraft payloads to study the long-term effects of various gravity and radiation environments on life. A CES is a useful spacecraft payload because of the scarcity and high value of mass in space. Resupplying the payloads with products from Earth and disposing of waste byproducts are not required. Also, CESs do not require flight crew attention so they can function for long durations on manned and unmanned spacecraft. CESs that are capable of supporting mammals significantly reduce the costs of space habitats enabling very long-term research of mammals subject to various gravity and radiation levels. CESs hold the prospect of permanently establishing life beyond Earth; initially with microbes, plants, and small animals, but ultimately in CESs with humans.

Orbiting Modular Artificial-Gravity Spacecraft (OMAGS)

OMAGS is a fractional gravity spacecraft design concept for CES payloads and is depicted in figures 11 and 12. It is a cislunar spacecraft with a 150cm-radius centrifuge. This centrifuge has a 2-ton bioscience payload capacity that produces artificial gravity by rotating 24 CESMs totaling 3,000 liters in volume. The bioscience research enabled can vary by each CESM and cover areas of fractional gravity, bioregenerative life support, and deep-space radiation-effect mitigation on the communities of biota in each CESM, including the microbiomes inside the multicellular organisms in the CESMs.

The spacecraft mission design is for a minimum of 5 years, but could extend much longer to observe the long-term effects of deep-space radiation and fractional gravity on biota communities from microbes to small mammals. The Voyager 1 and 2 spacecraft were both launched in 1977 and are still operational after 40 years. The longer an OMAGS-like spacecraft operates, the more valuable the data is from the CES payloads since the organism populations will have had more time to adapt and evolve to the space environment.

Figure 11: Orbiting Modular Artificial-Gravity Spacecraft (OMAGS) Preliminary Concept

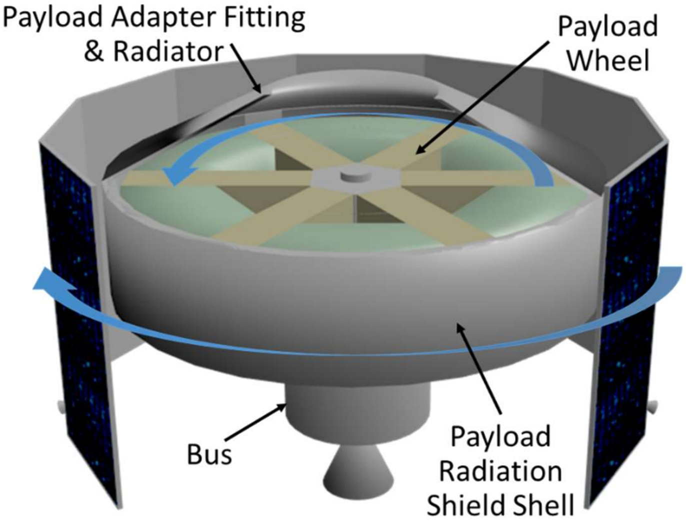


Figure 12: Orbiting Modular Artificial-Gravity Spacecraft Concept Cutaway View

The primary factors limiting mission duration are propellant and radiation shielding. For a fixed launch mass, these two factors can be traded to optimize the mission.

Although not depicted in this design, an OMAGS-like spacecraft could be configured as a Lander for long-term operation on Phobos, Deimos, or an asteroid. Doing so would eliminate the need for propellant after landing, provide additional radiation shielding and minute gravity, but would require additional communication considerations, such as using a relay, and larger solar panels that could unfold to compensate for the loss of solar power due to the rotation of the moon or asteroid.

The Spacecraft and Payload Centrifuge Wheel counter-rotate resulting in net zero angular momentum and zero gyroscopic forces. The spacecraft mass without the Payload Centrifuge Wheel is ~12 times more than the Payload Centrifuge Wheel mass so the spacecraft counter-rotates an order of magnitude more slowly than the Payload Centrifuge Wheel. This design enables the following important spacecraft operational characteristics, which significantly reduce propellant required for operations reducing overall mass and/or extending mission life:

- Artificial-gravity levels of the CESs can be changed without requiring propellant to change the spacecraft total angular momentum.
- The spacecraft attitude can be changed without having to compensate for gyroscopic forces of the Payload Centrifuge.

Artificial Gravity (AG)

The spacecraft generates Centripetal Acceleration (a_c) by rotating the Payload Centrifuge Wheel. a_c is conserved due to the Law of Conservation of Angular Momentum and changes linearly with radius, but changes quadratically with RPM according to the following formula:

$$a_c = v_T^2/r = (\mathrm{RPM}\ \pi)^2 r/900$$

where:

a_c (m/s^2) = the artificial-gravity level at the Payload floor due to centripetal acceleration
v_T (m/s) = the tangential velocity at the Payload floor
r (m) = radius, the distance from the Payload floor to the axis of rotation
RPM = the Centrifuge Wheel Revolutions Per Minute = $30v_T/\pi r$

An OMAGS artificial-gravity example is shown in table 6 for Level 0 CESMs at 24.4 RPM:

$$\text{Earth gravity} = 1g = 9.8(\mathrm{m/s^2}) = (24.4\pi)^2 \times 1.5(\mathrm{m})/900$$

Table 6: OMAGS Artificial Gravity Intensity by Centrifuge Module Level

RPM	Level 0 g	Level 1 g	Level 2 g	Level 3 g
24.4	1.00	0.80	0.60	0.20
14.0	0.33	0.26	0.20	0.13

OMAGS CES Payload Centrifuge

As noted in table 6 and shown in figure 13, the OMAGS Centrifuge simultaneously supports four artificial gravity intensities. In the Centrifuge, the lowest level 0 is at the bottom of the rim modules denoted R1 to R6. Moving upwards is essentially moving toward the hub from the rim. Each Spoke CESM is denoted by the Spoke # (1-6) followed by the level # (1-3), i.e., (SxLy) where x = Spoke # and y = Level #.

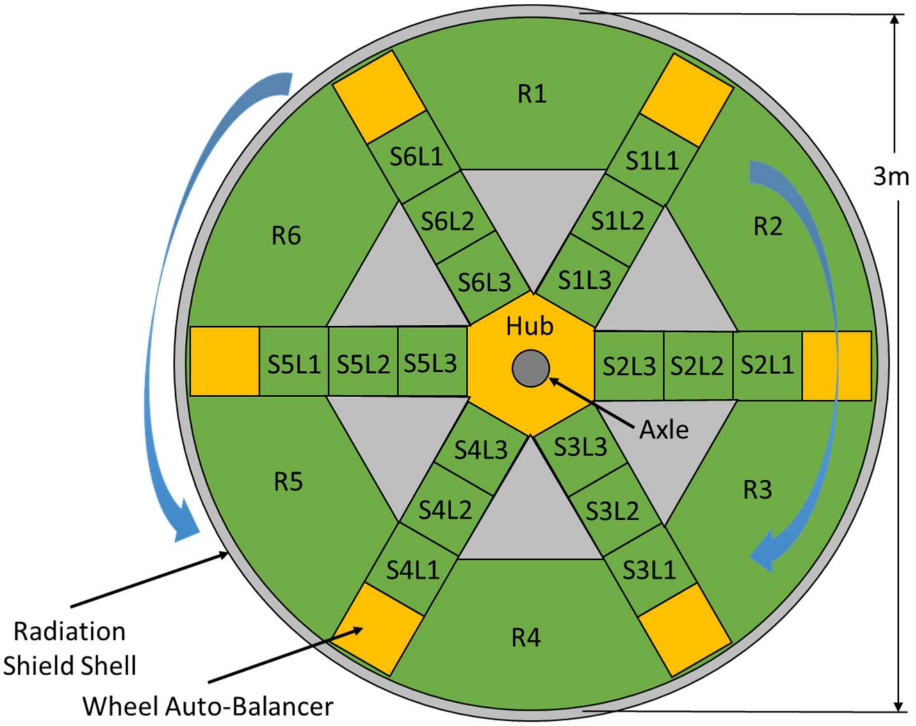


Figure 13: OMAGS Payload Centrifuge Wheel CESM Layout Top-View

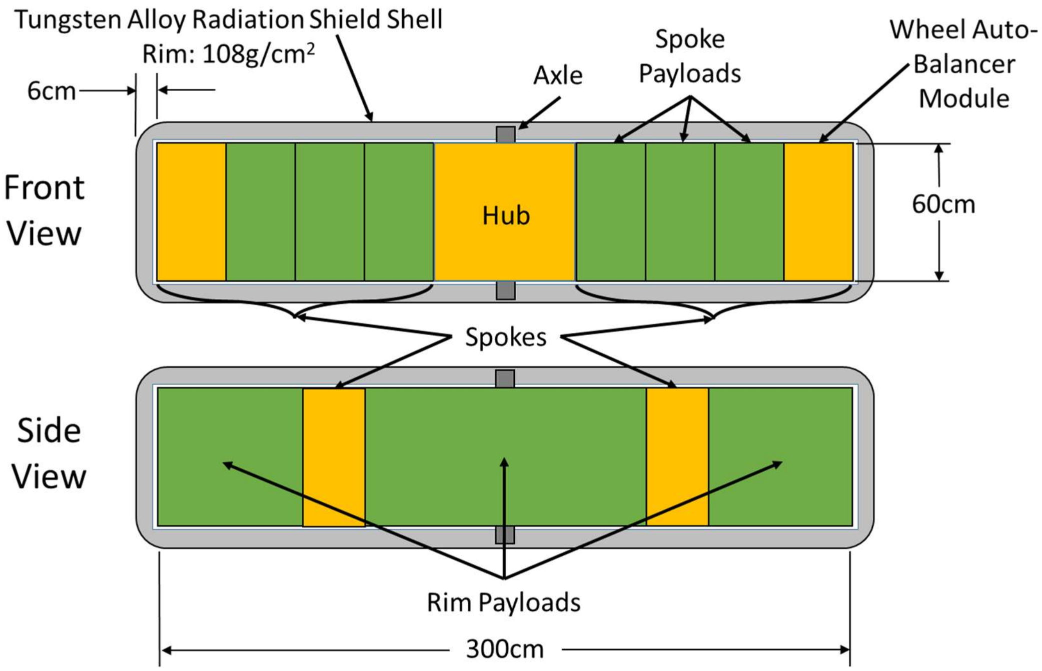


Figure 14: OMAGS Centrifuge Wheel CESM Layout Front and Side Cutaway-Views

As shown in figures 13 and 14, the OMAGS Centrifuge consists of:

- 6 Rim Payloads (R1-6)
- 18 Spoke Payloads (S[1-6]L[1-3])

- 6 Wheel Auto-Balancers
- Avionics Hub
- Axle
- Radiation Shield Shell

In addition to the gravity level of a CESM position, the proximity between CESMs in the same CES should be considered. The CESMs shown in figure 13 can be interconnected in a variety of ways to enable controlled transfer of their contents, but these connections are not shown. Adjacent CESMs can have direct connections, but CESMs that are further apart can be directly connected by piping.

The most flexible design would fully-connect all the CESMs with each other, but for direct connections that would require n(n-1)/2 connections where n is the number of CESMs; which in this case would require 276 direct connections since n=24. Far fewer connections are needed if indirect connections can be used whenever possible; i.e., by permitting two CESMs in the same CES to be connected by a path that passes through one or more intermediary CESMs. Generally, the design layout should minimize the piping required.

The 6 Wheel Auto-Balancers shown in figure 13 are used to dynamically keep the centrifuge center of gravity at the center of its axis, since the contents of each CESM, e.g., water, animals, can move internally and may transfer between CESMs. However, this balancing can be accomplished by other means if preferable. If the centrifuge is not kept balanced, it will wobble at the RPM rate causing slosh within the CESMs and other undesirable effects.

Payload Modules

The OMAGS spacecraft accommodates the following CES payload modules:

- (6) rim 350-liter payloads at 100% nominal AG
- (6) spoke 54-liter payloads at 80% nominal AG
- (6) spoke 54-liter payloads at 60% nominal AG
- (6) spoke 54-liter payloads at 40% nominal AG

The cutaway views of the rim and spoke modules are illustrated in figures 15 and 16 respectively.

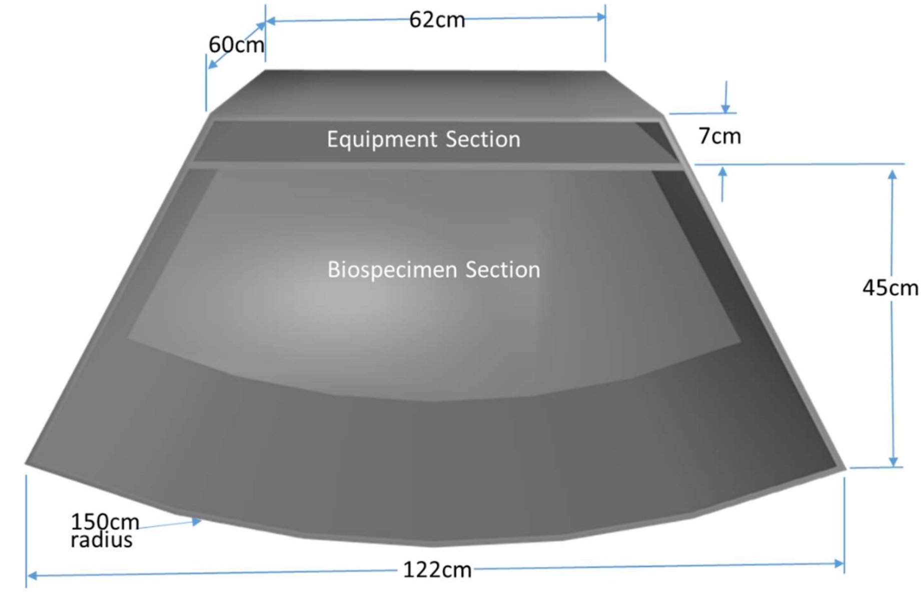


Figure 15: OMAGS Centrifuge Wheel CES Rim Module Layout Top Cutaway-View

Module Capacity: 350 liter (92 gallons) volume, including 27 liter equipment section

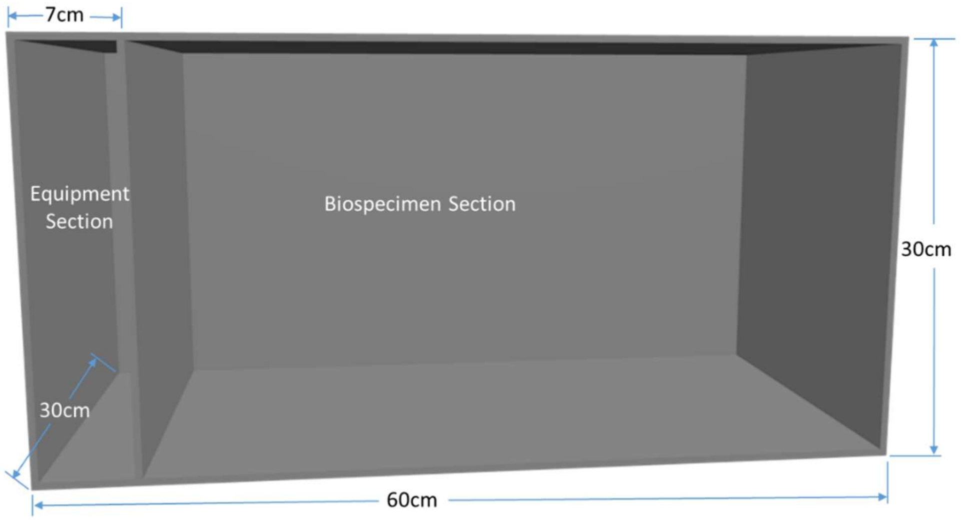


Figure 16: OMAGS Centrifuge Wheel CES Spoke Module Layout Side Cutaway-View

Module Capacity: 54 liter (14.3 gallons) volume, including 12.6 liter equipment section

Multi-Payload Module Rationale

Although the CESMs can be connected with controlled mass flow and organism exchange between the CESMs, the following reasons support keeping CESMs independent:

- Increase Experiment Robustness by increasing the system flexibility to maintain the viability of the payloads
- Increase Experiment Variety by being capable of addressing multiple science questions
- Increase Experiment Repeatability
- Increase Experiment Biospecimen Separation
- Increase Experiment Equipment Redundancy
- Vary radiation shielding of otherwise identical payloads
- Vary gravity level of otherwise identical payloads
- Increase number of stakeholders, e.g., multiple payload science organizations

If needed, CESMs can be connected during operation as long as the connection paths have been planned for as previously discussed.

Modular Design Approach

The long-term benefits of a modular design approach include that it scales up for much larger spacecraft centrifuges that can be incrementally assembled, repaired, and upgraded in space; along with operating both ground analogue module counterparts and their space-rated versions on Earth prior to their deployment in space (Dorais, 2016).

Conversely, smaller, low-cost versions of OMAGS spacecraft can be produced, such as by using 1-liter module-sized CubeSats covered by solar cells as shown in figure 17 where each module is a 10 x 10 x 10cm cube.

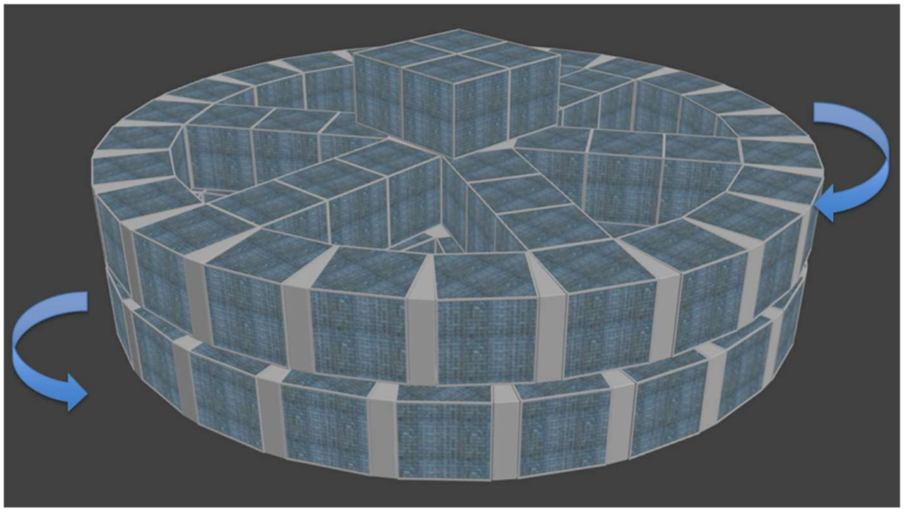


Figure 17: A CubeSat OMAGS Bioscience Testbed Design Concept

This design is 1m in diameter and the payload is two counter-rotating rings, each comprised of 42 CubesSats for a total payload capacity of 84 liters. The above design has very little radiation shielding and would have a relatively short mission life in LEO. Its primary value is as a testbed and for educational purposes. General information and developer specifications on CubeSats are available at: http://www.cubesat.org.

Summary

An adjustably-autonomous intelligent systems approach for developing Closed Ecosystems (CESs) was presented, which included describing a design concept and preliminary design details for the Controlled Closed-Ecosystem Development System (CCEDS) and the Orbiting Modular Artificial-Gravity Spacecraft (OMAGS). The paper is divided into three sections: CESs, the CCEDS Design Concept, and Orbiting Fractional-Gravity Closed Ecosystems OMAGS design concept.

The first section briefly describes Closed EcoSystems (CESs), complex adaptive systems, biomes, microbial microbiomes, and their relevance for the study of astrobiology. This section also discusses initial efforts in the development of Closed Environment Life Support Systems for sustainable communities in space and on Earth. This section concludes with a discussion of the bioregenerative life support system challenge and the corresponding consequences due to the inverse relationship of the very small human biomass/non-human biomass ratio overall on the Earth with respect to the extremely large human biomass/non-human-biomass ratio found in cities and the International Space Station.

The second section describes the CCEDS design concept, which consists of a population of independent CESs, each CES being a controlled colony of interconnected CES Modules (CESMs), continually generating data for an intelligent system that operates the CESs and their CESMs. A variety of CESM types and their uses are briefly described. The CCEDS intelligent system uses an evolutionary computation algorithm described in this section to develop and optimize these CESs to increase their viability duration and the size of the animals they support with the ultimate goal to support populations of humans, both on Earth and in space. The CCEDS architecture, its five control subsystems, and its five evolutionary computation levels are also discussed. The section concludes with a discussion of several CCEDS design strategies.

The third section summarizes the OMAGS design concept for a spacecraft with a payload consisting of CESs in an orbiting spacecraft centrifuge that operates for at least 5 years. The spacecraft concept is described including its 150cm-radius centrifuge with a 2 ton & 3,000 liter bioscience payload capacity for 24 CESMs. The centrifuge design has four physical levels for its CESMs, each level subject to a different fractional gravity level. This section presents the spacecraft benefits of being designed and operated such that the spacecraft and payload centrifuge wheel counter-rotate resulting in net zero angular momentum and zero gyroscopic forces. Artificial-gravity generation by centripetal acceleration is also discussed. This section concludes by showing the external specifications of the CESMs and their layout in the centrifuge, followed by discussing the multi-payload module and modular design approach rationales.

In tandem, the CCEDS and OMAGS systems can be used to foster gravitational ecosystem research for developing sustainable communities in space and on Earth.

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Appendix A: Abbreviations and Acronyms

Acronym	Definition
a_c	Centripetal Acceleration
AG	Artificial Gravity
C	centigrade
CDR	Cloud Data Repository
CCEDS	Close Ecosystem Development System
CES	Closed EcoSystem
CESM	Closed EcoSystem Module
cm	centimeter
CPU	Central Processing Unit
DNA	DeoxyriboNucleic Acid
doi	Digital Object Identifier
EC	Evolutionary Computation
g	Gravity-level at surface of Earth in (m/s^2)
GPS	Global Positioning System
GPU	Graphics Processing Unit
Gt C	Gigatonnes of Carbon
h	hour
kg	kilogram
LEO	Low Earth Orbit
m	meters
NASEM	National Academies of Sciences, Engineering, and Medicine
OMAGS	Orbiting Modular Artificial-Gravity Spacecraft
OPE	Optimizing Planner and Executive
PCES	Partially Closed EcoSystem
PRPs	Pattern Recognition Processors
r	radius of the Centrifuge
Rx	Rim module position in Centrifuge where x is the rim position #
RPM	Revolutions Per Minute
s	seconds
SxLy	Spoke module position in Centrifuge where x is the spoke # and y is the level #
USB	Universal Serial Bus
v_T	Tangential Velocity at the payload module floor