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Advanced Life Support System Simulation

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Abstract

The effective automatic control of Advanced Life Support Systems (ALSS) is a crucial component in space exploration. An ALSS is typically a coupled dynamical system: deterministic components that when coupled cause the overall behavior of the system very difficult to predict. We have implemented an ALSS simulator that models the basic processes occurring in the Bioregenerative Planetary Life Support System Test Complex (BIO-Plex) developed by NASA Johnson Space Center (Barta, Castillo & Fortson 1999, Kortenkamp, Bonasso & Subramanian 2001, Tri 1999). In this technical report, we present a mathematical description of our simulator and mathematical definitions of the optimization goals, the control strategies, and fitness functions used in previous work (Wu & Garibay 2003). We report findings on using a Genetic Algorithm (GA) and a Stochastic Hill-climber to learn control parameters for an ALSS simulation. We examine the behavior of these algorithms using different control strategies, fitness functions, population sizes, mutation rates, and most importantly, different representations: binary representation and three variants of the proportional representation (Wu & Garibay 2002) The GA using a proportional representation yields the best results throughout a wide range of settings for optimizing ALSS.

Keywords: Genetic algorithm, optimization, life support system control, resource allocation, proportional representation, evolutionary computation.

1 ALSS Mathematical Description

Informally, an ALSS simulation (Definition 1) is a coupled dynamical system with a set of internal simulation states (Definition 3), a control strategy (Definition 5) and a transition function (Definitions 6 to 10). The next step of a simulation (Definition 11) is calculated deterministically using the transition equations that compute the next simulation state from a current state and the current control variables provided by the control strategy. The learning problem is to find a controller or, equivalently, to find a set of control variables for each simulation step that maximizes the final value of a single simulation state or a function of these states. A simulation ends when the environment is not longer able to support human life (Definition 13). In this report, we describe three different optimization problems of interest: finding a control strategy that maximizes mission productivity (Definition 15), a control strategy that optimizes mission duration (Definition 16), and a control strategy that optimize both mission productivity and duration (Definition 17).

In (Wu & Garibay 2003) we define the ALSS mathematically without considering the storage system (Description 21) and the biomass equations (Description 22). In this report, we provide a full description of the ALSS simulator.

Definition 1 (ALSS) *Formally an* ALSS *simulation* $\mathcal{A}$ *is denoted by a 4-tuple:*

$$\mathcal{A} = \langle \mathcal{Q}, \vec{q_0}, \mathcal{C}, \delta_{\mathcal{C}} \rangle$$

where:

$\mathcal{Q}$ *is the set of simulation states,*

$\vec{q_0}$ *in* $\mathcal{Q}$ *is the initial state of the simulation,*

$\mathcal{C}$ *is the control strategy that defines a vector of control parameters for each simulation time step,*

$\delta_{\mathcal{C}}$ *finite set of transition equations*

Definition 2 (Simulation Variables) *Let* $\mathcal{V}$ *denote the set of all the variables associated with the simulation* $\mathcal{A}$*, then:*

$$\mathcal{V} \stackrel{def}{=} \{\vec{\mathbf{e}}, \vec{\mathbf{r}}, \vec{\mathbf{o}}, \vec{\mathbf{a}}, \vec{\mathbf{w}}\}$$

where:

$\vec{\mathbf{e}} \stackrel{def}{=} \langle \mathrm{e}_{energy}, \mathrm{e}_{air.o2}, \mathrm{e}_{air.co2}, \mathrm{e}_{water.clean}, \mathrm{e}_{water.dirty}, \mathrm{e}_{food}, \mathrm{e}_{science}, \mathrm{e}_{store.water}, \mathrm{e}_{store.food}, \mathrm{e}_{store.air.o2}, \mathrm{e}_{store.air.co2} \rangle$, *vector of* **environmental** *variables,*

$\vec{\mathbf{r}} \stackrel{def}{=} \langle \mathrm{r}_{status}, \mathrm{r}_{food}, \mathrm{r}_{water}, \mathrm{r}_{air.o2}, \mathrm{r}_{starvation}, \mathrm{r}_{dehydration}, \mathrm{r}_{asphyxiation} \rangle$, *vector of* **crew** *variables,*

$\vec{\mathbf{o}} \stackrel{def}{=} \langle \mathrm{o}_{status}, \mathrm{o}_{energy}, \mathrm{o}_{water}, \mathrm{o}_{low.energy}, \mathrm{o}_{low.water}, \mathrm{o}_{age}, \mathrm{o}_{biomass}, \mathrm{o}_{o2.released}, \mathrm{o}_{co2.absorved} \rangle$, *vector of* **crop** *variables,*

$\vec{\mathbf{a}} \stackrel{def}{=} \langle \mathrm{a}_{energy}, \mathrm{a}_{low.energy}, \mathrm{a}_{recovery.time} \rangle$, *vector of* **air recovery** *variables,*

$\vec{\mathbf{w}} \stackrel{def}{=} \langle \mathrm{w}_{in}, \mathrm{w}_{low.energy}, \mathrm{w}_{uptime}, \mathrm{w}_{potable}, \mathrm{w}_{energy} \rangle$, *vector of* **water recovery** *variables,*

Definition 3 (Simulation State) *A simulation state, $\vec{q}$ in $\mathcal{Q}$, is a particular assignment of values for all the simulation the variables in $\mathcal{V}$. The simulation state at time t is:*

$$\vec{q}_t \stackrel{def}{=} \langle \vec{\mathbf{e}}_t, \vec{\mathbf{r}}_t, \vec{\mathbf{o}}_t, \vec{\mathbf{a}}_t, \vec{\mathbf{w}}_t \rangle$$

Definition 4 (Initial State) *The initial simulation state denoted by $\vec{q_0}$ in $\mathcal{Q}$, is a defined as follows:*

$$\vec{q_0} \stackrel{def}{=} \langle \vec{\mathbf{e}}_0, \vec{\mathbf{r}}_0, \vec{\mathbf{o}}_0, \vec{\mathbf{a}}_0, \vec{\mathbf{w}}_0 \rangle$$

where:

$\vec{\mathbf{e}}_0 \stackrel{def}{=} \langle \mathrm{e}_{energy} = 10000, \mathrm{e}_{air.o2} = 3000 \times 0.2095, \mathrm{e}_{air.co2} = 3000 \times 0.0003, \mathrm{e}_{water.clean} = 10, \mathrm{e}_{water.dirty} = 0, \mathrm{e}_{food} = 4, \mathrm{e}_{science} = 0, \mathrm{e}_{store.water} = 500, \mathrm{e}_{store.food} = 500, \mathrm{e}_{store.air.o2} = 50000, \mathrm{e}_{store.air.co2} = 50000, \rangle$,

$\vec{\mathbf{r}}_0 \stackrel{def}{=} \langle \mathrm{r}_{status} = 1, \mathrm{r}_{food} = 0, \mathrm{r}_{water} = 0, \mathrm{r}_{air.o2} = 0, \mathrm{r}_{starvation} = 0, \mathrm{r}_{dehydration} = 0, \mathrm{r}_{asphyxiation} = 0 \rangle$,

$\vec{\mathbf{o}}_0 \stackrel{def}{=} \langle \mathrm{o}_{status} = 1, \mathrm{o}_{energy} = 0, \mathrm{o}_{water} = 0, \mathrm{o}_{low.energy} = 0, \mathrm{o}_{low.water} = 0, \mathrm{o}_{age} = 0, \mathrm{o}_{biomass} = 0, \mathrm{o}_{o2.released} = 0, \mathrm{o}_{co2.absorved=0} \rangle$,

$\vec{\mathbf{a}}_0 \stackrel{def}{=} \langle \mathrm{a}_{energy} = 0, \mathrm{a}_{low.energy} = 0, \mathrm{a}_{recovery.time} = 0 \rangle$,

$\vec{\mathbf{w}}_0 \stackrel{def}{=} \langle \mathrm{w}_{in} = 0, \mathrm{w}_{low.energy} = 0, \mathrm{w}_{uptime} = 10, \mathrm{w}_{potable} = 0, \mathrm{w}_{energy} = 0 \rangle$,

Definition 5 (Control Strategy) *Let $\mathcal{C}$ denote a control strategy and be defined as follows:*

$$\mathcal{C} \stackrel{def}{=} \left\{ \vec{\mathbf{c}}^{\,t} \;\middle|\; (0 \le t \le T_{max}) \bigwedge t \in N \right\}$$

where:

$\vec{\mathbf{c}}^{\,t} \stackrel{def}{=} \langle \mathrm{c}^t_{energy.to.air}, \mathrm{c}^t_{energy.to.water}, \mathrm{c}^t_{energy.to.food}, \mathrm{c}^t_{water.to.crew}, \mathrm{c}^t_{water.to.crops}, \mathrm{c}^t_{activity.level}, \mathrm{c}^t_{use.store.air}, \mathrm{c}^t_{use.store.water}, \mathrm{c}^t_{use.store.food}, \rangle$ *is the vector of* **control** *values for time* t*,*

$\mathcal{C} \in \mathbf{C}$, $\mathbf{C}$ *is the set of all posible control strategies.*

Definition 6 (Transition Equations) *The set of transition equations denoted by* $\delta_{\mathcal{C}}$*, defines how to obtain the next simulation state* $(t+1)$ *from the current state* (t) *for a given control strategy* $\mathcal{C}$*. The simulation,* $\mathcal{A}$*, is a coupled dynamical system with four components: crew, crops, air revitalization, water revitalization, and storage system. Therefore we have five sets of equations:*

$$\delta_{\mathcal{C}} \stackrel{def}{=} \langle \delta_{\mathcal{C}_{crew}}, \delta_{\mathcal{C}_{crops}}, \delta_{\mathcal{C}_{airRevitalization}}, \delta_{\mathcal{C}_{waterRevitalization}}, \delta_{\mathcal{C}_{storage}} \rangle$$

where definitions for $\delta_{\mathcal{C}_{crew}}$, $\delta_{\mathcal{C}_{crops}}$, $\delta_{\mathcal{C}_{airRevitalization}}$, $\delta_{\mathcal{C}_{waterRevitalization}}$, $\delta_{\mathcal{C}_{storage}}$ *are given below.*

Definition 7 (Crew Equations) $\delta_{\mathcal{C}_{crew}}$*:*

$$(\mathrm{r}_{status})_{t+1} = \begin{cases} 0 & \textit{if } [(\mathrm{r}_{status})_t = 0] \\ & \vee [(\mathrm{r}_{starvation})_t > \mathrm{R}_{F.Del}] \\ & \vee [(\mathrm{r}_{dehydration})_t > \mathrm{R}_{W.Del}] \\ & \vee [(\mathrm{r}_{asphyxiation})_t] > \mathrm{R}_{A.Del}], \\ (\mathrm{r}_{status})_t + & \\ -0.01 \times (\mathrm{r}_{status})_t \times [|(\mathrm{r}_{food})_t < 0.25 \times \mathrm{R}_{F.Req}|] & \\ -0.02 \times (\mathrm{r}_{status})_t \times [|(\mathrm{r}_{water})_t < 0.25 \times \mathrm{R}_{W.Req}|] & \\ -0.1 \times (\mathrm{r}_{status})_t \times [|(\mathrm{r}_{air.o2})_t < 0.25 \times \mathrm{R}_{A.Req}|] & \textit{otherwise.} \end{cases}$$

$$(\mathrm{r}_{starvation})_{t+1} = \begin{cases} (\mathrm{r}_{starvation})_t + 1 & \textit{if } [(\mathrm{r}_{food})_t < 0.25 \times \mathrm{R}_{F.Req}], \\ 0 & \textit{otherwise.} \end{cases}$$

$$(\mathrm{r}_{dehydration})_{t+1} = \begin{cases} (\mathrm{r}_{dehydration})_t + 1 & \textit{if } [(\mathrm{r}_{water})_t < 0.25 \times \mathrm{R}_{W.Req}], \\ 0 & \textit{otherwise.} \end{cases}$$

$$(\mathrm{r}_{asphyxiation})_{t+1} = \begin{cases} (\mathrm{r}_{asphyxiation})_t + 1 & \textit{if } [(\mathrm{e}_{air.o2})_t < 0.25 \times \mathrm{R}_{A.Req}], \\ 0 & \textit{otherwise.} \end{cases}$$

$$(\mathrm{e}_{air.o2})_{t+1} = \begin{cases} (\mathrm{e}_{air.o2})_t - 537.6/24 & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{SLEEP}], \\ (\mathrm{e}_{air.o2})_t - 832.8/24 & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{LOW}], \\ (\mathrm{e}_{air.o2})_t - 1200/24 & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{MED}], \\ (\mathrm{e}_{air.o2})_t - 1600.8/24 & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{HIGH}]. \end{cases}$$

$$(\mathrm{e}_{air.co2})_{t+1} = \begin{cases} (\mathrm{e}_{air.co2})_t + 643.2/24 & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{SLEEP}], \\ (\mathrm{e}_{air.co2})_t + 996.0/24 & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{LOW}], \\ (\mathrm{e}_{air.co2})_t + 1433.7/24 & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{MED}], \\ (\mathrm{e}_{air.co2})_t + 1910.4/24 & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{HIGH}]. \end{cases}$$

$$(\mathrm{e}_{water.clean})_{t+1} = \begin{cases} (\mathrm{e}_{water.clean})_t - 0.75 \times (\mathrm{r}_{water})_t & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{LOW}], \\ (\mathrm{e}_{water.clean})_t - 0.85 \times (\mathrm{r}_{water})_t & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{MED}], \\ (\mathrm{e}_{water.clean})_t - 0.95 \times (\mathrm{r}_{water})_t & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{HIGH}], \\ (\mathrm{e}_{water.clean})_t & \textit{otherwise.} \end{cases}$$

$$(\mathrm{e}_{water.dirty})_{t+1} = \begin{cases} (\mathrm{e}_{water.dirty})_t + 0.75 \times (\mathrm{r}_{water})_t & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{LOW}], \\ (\mathrm{e}_{water.dirty})_t + 0.85 \times (\mathrm{r}_{water})_t & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{MED}], \\ (\mathrm{e}_{water.dirty})_t + 0.95 \times (\mathrm{r}_{water})_t & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{HIGH}], \\ (\mathrm{e}_{water.dirty})_t & \textit{otherwise.} \end{cases}$$

$$(\mathrm{e}_{food})_{t+1} = \begin{cases} (\mathrm{e}_{food})_t - 0.75 \times (\mathrm{r}_{food})_t & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{LOW}], \\ (\mathrm{e}_{food})_t - 0.85 \times (\mathrm{r}_{food})_t & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{MED}], \\ (\mathrm{e}_{food})_t - 0.95 \times (\mathrm{r}_{food})_t & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{HIGH}], \\ (\mathrm{e}_{food})_t & \textit{otherwise.} \end{cases}$$

$$(\mathrm{e}_{science})_{t+1} = \begin{cases} (\mathrm{e}_{science})_t + 0.75 \times \mathrm{R}_{Number} \times \mathrm{R}_{SciFact} \times (\mathrm{r}_{status})_t & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{LOW}], \\ (\mathrm{e}_{science})_t + 0.85 \times \mathrm{R}_{Number} \times \mathrm{R}_{SciFact} \times (\mathrm{r}_{status})_t & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{MED}], \\ (\mathrm{e}_{science})_t + 0.95 \times \mathrm{R}_{Number} \times \mathrm{R}_{SciFact} \times (\mathrm{r}_{status})_t & \textit{if } [\mathrm{c}^t_{activity.level} = \textit{HIGH}], \\ (\mathrm{e}_{science})_t & \textit{otherwise.} \end{cases}$$

Where:

$$(\mathrm{r}_{water})_t = min[\mathrm{c}^t_{water.to.crew}, (\mathrm{e}_{water.clean})_t]$$

$$(\mathrm{r}_{food})_t = min[\mathrm{R}_{F.Req}, (\mathrm{e}_{food})_t]$$

$$(\mathrm{r}_{air.o2})_t = min[\mathrm{R}_{A.Req}, (\mathrm{e}_{air.o2})_t],$$

the following are constants: $\mathrm{R}_{F.Del}$*(crew food delay)* $= 120$, $\mathrm{R}_{W.Del}$*(crew water delay)* $= 72$, $\mathrm{R}_{A.Del}$*(crew air delay)* $= 3$, $\mathrm{R}_{F.Req}$*(crew food requirement)* $= 1/6$, $\mathrm{R}_{W.Req}$*(crew water requirement)* $= 1/6$, $\mathrm{R}_{A.Req}$*(crew air requirement)* $= 40000$, R_{Number}*(crew number)* $= 4$, *and* $\mathrm{R}_{SciFact}$*(crew science factor)* $= 1$. *We used the notation:* $[|p|] = 1$ *iff* p *is True,* $[|p|] = 0$ *otherwise.;* $min[A, B] = A$ *iff* $(A \leq B)$, $min[A, B] = B$ *otherwise.*

Definition 8 (Crop Equations) $\delta_{\mathcal{C}_{crops}}$*:*

$$(\mathrm{o}_{status})_{t+1} = \begin{cases} 0 & \text{if } [(\mathrm{o}_{status})_t = 0] \\ & \vee [(\mathrm{o}_{low.energy})_t > \mathrm{O}_{\mathrm{L.noE}}] \\ & \vee [(\mathrm{o}_{low.water})_t > \mathrm{O}_{\mathrm{L.noW}}], \\ (\mathrm{o}_{status})_t + & \\ -0.03 \times (\mathrm{o}_{status})_t \times [|(\mathrm{o}_{energy})_t < 0.25|] & \\ -0.01 \times (\mathrm{o}_{status})_t \times [|(\mathrm{o}_{water})_t < 0.25|] & \text{otherwise.} \end{cases}$$

$$(\mathrm{o}_{low.energy})_{t+1} = \begin{cases} (\mathrm{o}_{low.energy})_t + 1 & \text{if } [(\mathrm{o}_{energy})_t < 0.25], \\ 0 & \text{otherwise.} \end{cases}$$

$$(o_{low.water})_{t+1} = \begin{cases} (o_{low.water})_t + 1 & \text{if } [(o_{water})_t < 0.25], \\ 0 & \text{otherwise.} \end{cases}$$

$$(o_{age})_{t+1} = \begin{cases} 0 & \text{if } [\frac{(o_{age})_t}{24} > 88], \\ (o_{age})_t + 1 & \text{otherwise.} \end{cases}$$

$$(e_{energy})_{t+1} = \{(e_{energy})_t - (o_{energy})_t\}$$

$$(e_{water.clean})_{t+1} = \{(e_{water.clean})_t - (o_{water})_t\}$$

$$(e_{water.dirty})_{t+1} = \{(e_{water.dirty})_t + (o_{water})_t\}$$

$$(e_{food})_{t+1} = \begin{cases} (e_{food})_t + (o_{biomass})_t \times 0.05 \times (o_{status})_t & \text{if } [(o_{biomass})_t \geq 0], \\ (e_{food})_t & \text{otherwise.} \end{cases}$$

$$(e_{air.o2})_{t+1} = \{(e_{air.o2})_t + (o_{o2.released})_t \times (o_{status})_t\}$$

$$(e_{air.co2})_{t+1} = \{(e_{air.co2})_t + (o_{co2.absorved})_t \times (o_{status})_t\}$$

Where:

$$(o_{energy})_t = min[c^t_{energy.to.food}, (e_{energy})_t],$$

$$(o_{water})_t = min[c^t_{water.to.crops}, (e_{water.clean})_t],$$

and the following are constants: $O_{L.noW}$(crops life with no water) $= 120$, and $O_{L.noE}$(crops life with no energy) $= 168$.

Definition 9 (Air Revitalization System Equations) $\delta_{\mathcal{C}_{airRevitalization}}$:

$$(a_{low.energy})_{t+1} = \begin{cases} (a_{low.energy})_t + 1 & \text{if } [(a_{energy})_t < 0.25], \\ 0 & \text{otherwise.} \end{cases}$$

$$(a_{recovery.time})_{t+1} = \begin{cases} (a_{recovery.time})_t - 1 & \text{if } [(a_{energy})_t \geq 0.25] \wedge [(a_{recovery.time})_t > 0], \\ A_{T.rec} & \text{if } [(a_{low.energy})_t \geq A_{A.del}], \\ (a_{recovery.time})_t & \text{otherwise.} \end{cases}$$

$$(e_{air.o2})_{t+1} = \begin{cases} (e_{air.o2})_t + 50 \times (a_{energy})_t & \text{if } [(a_{recovery.time})_t = 0], \\ (e_{air.o2})_t & \text{otherwise.} \end{cases}$$

$$(e_{air.co2})_{t+1} = \begin{cases} (e_{air.co2})_t - 50 \times (a_{energy})_t & \text{if } [(a_{recovery.time})_t = 0], \\ (e_{air.co2})_t & \text{otherwise.} \end{cases}$$

$$(e_{energy})_{t+1} = \{(e_{energy})_t - (a_{energy})_t\}$$

Where:

$$(a_{energy})_t = min[c^t_{energy.to.air}, (e_{energy})_t],$$

and the following are constants: $A_{T.rec}$(air revitalization system startup time) $= 3$, and $A_{A.del}$(air revitalization systems maximum energy delay time) $= 1$.

Definition 10 (Water Revitalization System Equations) $\delta_{\mathcal{C}_{waterRevitalization}}$*:*

$$(\mathrm{w}_{uptime})_{t+1} = \begin{cases} 0 & \textit{if } [(\mathrm{w}_{low.energy})_t > \mathrm{W}_{T.sdo}], \\ (\mathrm{w}_{uptime})_t + 1 & \textit{otherwise.} \end{cases}$$

$$(\mathrm{w}_{in})_{t+1} = \{(\mathrm{w}_{in})_t + (\mathrm{e}_{water.dirty})_t - (\mathrm{w}_{potable})_t\}$$

$$(\mathrm{w}_{potable})_{t+1} = \begin{cases} 0 & \textit{if } [(\mathrm{w}_{energy})_t < 0.25], \\ \mathrm{W}_{W.rra} \times (\mathrm{w}_{in})_t & \textit{if } [((\mathrm{w}_{uptime})_t/\mathrm{W}_{T.wup}) \geq 1], \\ ((\mathrm{w}_{uptime})_t/\mathrm{W}_{T.wup}) \times \mathrm{W}_{W.rra} \times (\mathrm{w}_{in})_t & \textit{otherwise.} \end{cases}$$

$$(\mathrm{w}_{low.energy})_{t+1} = \begin{cases} (\mathrm{w}_{low.energy})_t + 1 & \textit{if } [(\mathrm{w}_{energy})_t < 0.5], \\ 0 & \textit{otherwise.} \end{cases}$$

$$(\mathrm{e}_{water.dirty})_{t+1} = 0$$

$$(\mathrm{e}_{water.clean})_{t+1} = \{(\mathrm{e}_{water.clean})_t + (\mathrm{w}_{potable})_t\}$$

$$(\mathrm{e}_{energy})_{t+1} = \{(\mathrm{e}_{energy})_t - (\mathrm{w}_{energy})_t\}$$

Where:

$$(\mathrm{w}_{energy})_t = min[\mathrm{c}^t_{energy.to.water}, (\mathrm{e}_{energy})_t],$$

and the following constants: $\mathrm{W}_{T.wup}$*(water revitalization system warmup time)* $= 10$, $\mathrm{W}_{T.sdo}$*(water revitalization system shutdown time)* $= 5$, *and* $\mathrm{W}_{W.rra}$*(water recovery rate)* $= 0.97$.

Definition 11 (Simulation Step) *Applying the transition equations* $\delta_{\mathcal{C}}$ *to the state* $\vec{q}_t$ *we obtain the next state* $\vec{q}_{t+1}$ *of the simulation* $\mathcal{A}$

$$\vec{q}_{t+1} \stackrel{def}{=} \delta_{\mathcal{C}}(\vec{q}_t)$$

where:

$$\delta_{\mathcal{C}}(\vec{q}_t) \stackrel{def}{=} \delta_{\mathcal{C}_{waterRevitalization}}(\delta_{\mathcal{C}_{airRevitalization}}(\delta_{\mathcal{C}_{crops}}(\delta_{\mathcal{C}_{storage}}(\delta_{\mathcal{C}_{crew}}(\vec{q}_t)))))$$

Definition 12 (Simulation t Steps) *The reflexive and transitive closure of* $\delta_{\mathcal{C}}$ *is denoted by* $\hat{\delta_{\mathcal{C},t}}$*:*

$$\vec{q}_t \stackrel{def}{=} \hat{\delta_{\mathcal{C},t}}(\vec{q}_0)$$

Definition 13 (Simulation End time) *Simulation* $\mathcal{A}$ *ends when the environment variable crew status,* r_{status}*, is equal to zero (the environment is not longer able to support human life) or when the limit time for the simulation* T_{max} *is reached. We denote this ending time as* ${t_{Final}}^{\mathcal{A}}$*,*

$${t_{Final}}^{\mathcal{A}} \stackrel{def}{=} \min_{t \leq T_{max}} \left[\vec{q}_t = \hat{\delta_{\mathcal{C},t}}(\vec{q}_0) \bigwedge (\mathrm{r}_{status})_t = 0\right]$$

where:

$(\mathrm{r}_{status})_t \in \vec{q_t}$, $\vec{q_t} \in \mathcal{Q}$, *and* $\mathcal{A} = \langle \mathcal{Q}, \vec{q_0}, \mathcal{C}, \delta_{\mathcal{C}} \rangle$.

Definition 14 (Final State) *The final state of simulation $\mathcal{A}$ is denoted by $\vec{q}^{\mathcal{A}}_{t_{Final}}$ and defined as follows:*

$$\vec{q}^{\mathcal{A}}_{t_{Final}} \stackrel{def}{=} \left\{ \vec{q_t} \;\middle|\; \vec{q_t} = \hat{\delta_{\mathcal{C},t}}(\vec{q_0}) \bigwedge t = {t_{Final}}^{\mathcal{A}} \right\}$$

where:

$\vec{q}^{\mathcal{A}}_{t_{Final}}, \vec{q_t} \in \mathcal{Q}$, *and* $\mathcal{A} = \langle \mathcal{Q}, \vec{q_0}, \mathcal{C}, \delta_{\mathcal{C}} \rangle$.

1.1 Optimization

Definition 15 (Optimization 1: maximize mission productivity) *Let $\mathcal{C}_{Opt1}$ denote the optimal control strategy for maximizing mission productivity, and be defined as follows:*

$$\mathcal{C}_{Opt1} \stackrel{def}{=} \left\{ \mathcal{C}_j \;\middle|\; \left(\underset{\mathcal{C}_i \,\in\, \mathbf{C}}{\forall} \right) \left[(\mathrm{e}_{science})^{\mathcal{A}_j}_{t_{Final}} \geq (\mathrm{e}_{science})^{\mathcal{A}_i}_{t_{Final}} \right] \right\}$$

where

$\mathcal{C}_{Opt1}, \mathcal{C}_i$, *and* $\mathcal{C}_j \in \mathbf{C}$; $\mathcal{A}_i = \langle \mathcal{Q}, \vec{q_0}, \mathcal{C}_i, \delta_{\mathcal{C}i} \rangle$; $\mathcal{A}_j = \langle \mathcal{Q}, \vec{q_0}, \mathcal{C}_j, \delta_{\mathcal{C}j} \rangle$; $(\mathrm{e}_{science})^{\mathcal{A}_i}_{t_{Final}} \in \vec{q}^{\mathcal{A}_i}_{t_{Final}}$; $(\mathrm{e}_{science})^{\mathcal{A}_j}_{t_{Final}} \in \vec{q}^{\mathcal{A}_j}_{t_{Final}}$; *and* $\mathbf{C}$ *is the set of all posible control strategies;*

Definition 16 (Optimization 2: maximize mission duration) *Let $\mathcal{C}_{Opt2}$ denote the optimal control strategy for maximizing mission duration, and be defined as follows:*

$$\mathcal{C}_{Opt2} \stackrel{def}{=} \left\{ \mathcal{C}_j \;\middle|\; \left(\underset{\mathcal{C}_i \,\in\, \mathbf{C}}{\forall} \right) \left[{t_{Final}}^{\mathcal{A}_j} \geq {t_{Final}}^{\mathcal{A}_i} \right] \right\}$$

where

$\mathcal{C}_{Opt2}, \mathcal{C}_i$, *and* $\mathcal{C}_j \in \mathbf{C}$; $\mathcal{A}_i = \langle \mathcal{Q}, \vec{q_0}, \mathcal{C}_i, \delta_{\mathcal{C}i} \rangle$; $\mathcal{A}_j = \langle \mathcal{Q}, \vec{q_0}, \mathcal{C}_j, \delta_{\mathcal{C}j} \rangle$; *and* $\mathbf{C}$ *is the set of all posible control strategies;*

Definition 17 (Optimization 3: maximize mission productivity and duration) *Let $\mathcal{C}_{Opt3}$ denote the optimal control strategy for maximizing mission productivity and mission duration, and be defined as follows:*

$$\mathcal{C}_{Opt3} \stackrel{def}{=} \left\{ \mathcal{C}_j \;\middle|\; \left(\underset{\mathcal{C}_i \,\in\, \mathbf{C}}{\forall} \right) \left[(\mathrm{e}_{science})^{\mathcal{A}_j}_{t_{Final}} + 3 \times {t_{Final}}^{\mathcal{A}_j} \geq (\mathrm{e}_{science})^{\mathcal{A}_i}_{t_{Final}} + 3 \times {t_{Final}}^{\mathcal{A}_i} \right] \right\}$$

where

$\mathcal{C}_{Opt3}, \mathcal{C}_i,$ *and* $\mathcal{C}_j \in \mathbf{C}$*;* $\mathcal{A}_i = \langle \mathcal{Q}, \vec{q_0}, \mathcal{C}_i, \delta_{\mathcal{C}i} \rangle$*;* $\mathcal{A}_j = \langle \mathcal{Q}, \vec{q_0}, \mathcal{C}_j, \delta_{\mathcal{C}j} \rangle$*;* $(\mathrm{e}_{science})^{\mathcal{A}_i}_{t_{Final}} \in \vec{q}^{\mathcal{A}_i}_{t_{Final}}$*;* $(\mathrm{e}_{science})^{\mathcal{A}_j}_{t_{Final}} \in \vec{q}^{\mathcal{A}_j}_{t_{Final}}$*; and* $\mathbf{C}$ *is the set of all posible control strategies;*

1.2 Fitness

The fitness value of an individual—n vectors of control variables—is determined by running the ALSS simulation with the individual's n vectors and control strategy Γ_n. We use the following fitness measures for all experiments:

1. The total amount of "science" produced by the crew when the simulation ends, when optimizing mission productivity (Definition 18).
2. The number of simulation time steps at which the simulation ends, when optimizing mission duration (Definition 19).
3. A weighted addition of the previous two measures, when optimizing both (Definition 20).

Definition 18 (Fitness 1: mission productivity) *Let* $f_1(\mathcal{C}_k)$ *denote the fitness of the control strategy* $\mathcal{C}_k$ *while optimizing mission productivity in simulation* $\mathcal{A}_k$*, be defined as follows:*

$$f_1(\mathcal{C}_k) = \left\{ (\mathrm{e}_{science})^{\mathcal{A}_k}_{t_{Final}} \;\middle|\; (\mathrm{e}_{science})^{\mathcal{A}_k}_{t_{Final}} \in \vec{q}^{\mathcal{A}_k}_{t_{Final}} \bigwedge \mathcal{A}_k = \langle \mathcal{Q}, \vec{q_0}, \mathcal{C}_k, \delta_{\mathcal{C}k} \rangle \right\}$$

Definition 19 (Fitness 2: mission duration) *Let* $f_2(\mathcal{C}_k)$ *denote the fitness of the control strategy* $\mathcal{C}_k$ *while optimizing mission duration in simulation* $\mathcal{A}_k$*, be defined as follows:*

$$f_2(\mathcal{C}_k) = \left\{ t_{Final}{}^{\mathcal{A}_k} \;\middle|\; \mathcal{A}_k = \langle \mathcal{Q}, \vec{q_0}, \mathcal{C}_k, \delta_{\mathcal{C}k} \rangle \right\}$$

Definition 20 (Fitness 3: mission productivity and duration) *Let* $f_3(\mathcal{C}_k)$ *denote the fitness of the control strategy* $\mathcal{C}_k$ *while optimizing mission productivity and mission duration in simulation* $\mathcal{A}_k$*, be defined as follows:*

$$f_3(\mathcal{C}_k) = \left\{ (\mathrm{e}_{science})^{\mathcal{A}_k}_{t_{Final}} + 3 \times t_{Final}{}^{\mathcal{A}_k} \;\middle|\; (\mathrm{e}_{science})^{\mathcal{A}_k}_{t_{Final}} \in \vec{q}^{\mathcal{A}_k}_{t_{Final}} \bigwedge \mathcal{A}_k = \langle \mathcal{Q}, \vec{q_0}, \mathcal{C}_k, \delta_{\mathcal{C}k} \rangle \right\}$$

1.3 Storage System and Biomass

Definition 21 (Storage System Equations)

$$(\mathrm{e}_{store.air.o2})_{t+1} = \begin{cases} 0 & \textit{if } [\mathrm{c}^t_{use.store.air} = 1] \wedge [0 \leq (\mathrm{e}_{store.air.o2})_t < 50] \\ (\mathrm{e}_{store.air.o2})_t - 50 & \textit{if } [\mathrm{c}^t_{use.store.air} = 1] \wedge [(\mathrm{e}_{store.air.o2})_t \geq 50] \\ (\mathrm{e}_{store.air.o2})_t & \textit{otherwise.} \end{cases}$$

$$(\mathrm{e}_{air.o2})_{t+1} = \begin{cases} (\mathrm{e}_{air.o2})_t + (\mathrm{e}_{store.air.o2})_t & \textit{if } [\mathrm{c}^t_{use.store.air} = 1] \wedge [0 \leq (\mathrm{e}_{store.air.o2})_t < 50] \\ (\mathrm{e}_{air.o2})_t + 50 & \textit{if } [\mathrm{c}^t_{use.store.air} = 1] \wedge [(\mathrm{e}_{store.air.o2})_t \geq 50] \\ (\mathrm{e}_{air.o2})_t & \textit{otherwise.} \end{cases}$$

$$(\mathrm{e}_{store.water})_{t+1} = \begin{cases} 0 & \textit{if } [\mathrm{c}^t_{use.store.water} = 1] \\ & \wedge [0 \leq (\mathrm{e}_{store.water})_t < (4 \times \mathrm{S}_{F.water})] \\ (\mathrm{e}_{store.water})_t - (4 \times \mathrm{S}_{F.water}) & \textit{if } [\mathrm{c}^t_{use.store.water} = 1] \\ & \wedge [(\mathrm{e}_{store.water})_t \geq (4 \times \mathrm{S}_{F.water})] \\ (\mathrm{e}_{store.water})_t & \textit{otherwise.} \end{cases}$$

$$(\mathrm{e}_{water.clean})_{t+1} = \begin{cases} (\mathrm{e}_{water.clean})_t + (\mathrm{e}_{store.water})_t & \textit{if } [\mathrm{c}^t_{use.store.water} = 1] \\ & \wedge [0 \leq (\mathrm{e}_{store.water})_t < (4 \times \mathrm{S}_{F.water})] \\ (\mathrm{e}_{water.clean})_t + (4 \times \mathrm{S}_{F.water}) & \textit{if } [\mathrm{c}^t_{use.store.water} = 1] \\ & \wedge [(\mathrm{e}_{store.water})_t \geq (4 \times \mathrm{S}_{F.water})] \\ (\mathrm{e}_{water.clean})_t & \textit{otherwise.} \end{cases}$$

$$(\mathrm{e}_{store.food})_{t+1} = \begin{cases} 0 & \textit{if } [\mathrm{c}^t_{use.store.food} = 1] \\ & \wedge [0 \leq (\mathrm{e}_{store.food})_t < (4 \times \mathrm{S}_{F.food})] \\ (\mathrm{e}_{store.food})_t - (4 \times \mathrm{S}_{F.food}) & \textit{if } [\mathrm{c}^t_{use.store.food} = 1] \\ & \wedge [(\mathrm{e}_{store.food})_t \geq (4 \times \mathrm{S}_{F.food})] \\ (\mathrm{e}_{store.food})_t & \textit{otherwise.} \end{cases}$$

$$(\mathrm{e}_{food})_{t+1} = \begin{cases} (\mathrm{e}_{food})_t + (\mathrm{e}_{store.food})_t & \textit{if } [\mathrm{c}^t_{use.store.food} = 1] \\ & \wedge [0 \leq (\mathrm{e}_{store.food})_t < (4 \times \mathrm{S}_{F.food})] \\ (\mathrm{e}_{food})_t + (4 \times \mathrm{S}_{F.food}) & \textit{if } [\mathrm{c}^t_{use.store.food} = 1] \\ & \wedge [(\mathrm{e}_{store.food})_t \geq (4 \times \mathrm{S}_{F.food})] \\ (\mathrm{e}_{food})_t & \textit{otherwise.} \end{cases}$$

Where the following are constants: $\mathrm{S}_{F.water} = 1/24$, *and* $\mathrm{S}_{F.food} = 1/24$.

Definition 22 (Biomass Equations)

$$\mathrm{o}_{biomass} = 0, \mathrm{o}_{o2.released} = 0, \mathrm{o}_{co2.absorved=0}\mathrm{o}_{status} = 1, \mathrm{o}_{energy} = 0, \mathrm{o}_{water} = 0, \mathrm{o}_{low.energy} = 0, \mathrm{o}_{low.water} = 0, \mathrm{o}_{ag}$$

$$
\begin{aligned}
o_{biomass} &= (a_1 + (a_2 \times B_{frac.light} \times B_{plant.age}) + (a_3 \times (B_{frac.light} \times B_{plant.age})^2)) \\
&\quad \times \frac{B_{grow.rate}}{B_{grow.rate.coef}} \times \frac{B_{co2}}{B_{co2.coef}} \times \frac{B_{crop.density}}{B_{crop.nom.density}} \times B_{tray.area} \\
o_{co2.absorved} &= \frac{o_{biomass}}{0.723} \\
o_{o2.released} &= o_{co2.absorved} \times 0.727
\end{aligned}
$$

Where:

$$B_{\text{grow.rate}} = \beta_0 + \beta_1 \times (240 \times o_{energy}) + \beta_2 \times (240 \times o_{energy})^2$$

$$B_{\text{co2}} = 72 - (78.89 \times e^{-\left(\frac{B_{\text{co2.concentration}}}{400}\right)})$$

$$B_{\text{frac.light}} = \frac{B_{\text{light.per}}}{B_{\text{nominal.light.per}}}$$

$$B_{\text{plant.age}} = \left(\frac{o_{age}}{24}\right) \times 0.63529$$

$$B_{\text{grow.rate.coef}} = \beta_0 + \beta_1 \times (B_{\text{nominal.light.intensity}}) + \beta_2 \times (B_{\text{nominal.light.intensity}})^2$$

$$B_{\text{co2.coef}} = 72 - (78.89 \times e^{-\left(\frac{B_{\text{nominal.co2.concent}}}{400}\right)})$$

$$B_{\text{co2.concentration}} = \frac{\frac{e_{air.co2}}{\text{CO2W}}}{\frac{e_{air.co2}}{\text{CO2W}} + \frac{e_{air.o2}}{\text{O2W}} + \frac{e_{air.N2}}{\text{N2W}} + \frac{e_{air.H2O}}{\text{H2OW}}}$$

and, $B_{\text{light.per}} = 20$, $B_{\text{nominal.light.per}} = 20$, $\beta_0 = -7.6146$, $\beta_1 = 0.1114$, $\beta_2 = -0.00002149$, $B_{\text{nominal.light.intensity}} = 1204$, $B_{\text{nominal.co2.concent}} = 2000$, $CO2W = 44$, $O2W = 32$, $N2W = 28$, $H2OW = 18$, $B_{\text{crop.nom.density}} = 2000$, $B_{\text{crop.density}} = 2000$, $B_{\text{tray.area}} = 4$, $a_1 = ((0.3056 \times T) - 3.782)$, $a_2 = ((0.2515 \times T) - 0.24696)$, $a_3 = (0.06175 - (0.006866 \times T))$, and $T = 22$.

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