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ABSTRACT

To allow for the assessment of synergistic subsystem interactions during the conceptual design phase of manned spacecraft and space stations, an existing software tool was improved to permit integrated modeling and simulation of a space station's life support system and attitude and orbit control system. This facilitates early estimation of potential reductions in resupply mass – and life-cycle cost – as well as the assessment of increases in operational flexibility through incorporation of synergisms into the conceptual design. The created interactive tool is based on a user-friendly graphical programming language and can therefore be used by conceptual designers and engineering students alike.

INTRODUCTION

Reducing the resupply mass is one of the main ways of cutting life-cycle cost for permanently manned space platforms such as the International Space Station (ISS) or its successors [1].

One promising approach for achieving this goal is the use of synergies derived from linking subsystems that are related by common functions or common process fluids [8]. Taking into account possible interactions between these subsystems early in the conceptual design phase of a space station facilitates the tapping of synergistic potential during detailed design later on. User-friendly modeling and interactive simulation can also serve to demonstrate the dynamic behavior of subsystems for systems engineering education.

The subsystems for attitude and orbit control (AOCS) and for environmental control and life support (ECLSS) are especially well-suited as candidates for synergistic linkages, due to the similarity of species that can be used in both subsystems (water, oxygen, hydrogen), and due to their high individual shares in any space station's logistics budget [5].

In the case of the Space Station Freedom program, for example, designers planned to use resistojet thrusters fueled with ECLSS wastewater for altitude control [12]. Moreover, arcjet thrusters fueled by water steam are currently being developed, thus increasing the potential for introducing synergistic linkages between ECLSS and AOCS [9].

To enable a design team to estimate possible gains from introducing synergistic couplings, and to help design engineers and engineering students understand the complex dynamics of such a synergistic system, a computer simulation tool was created which is described in this paper. This tool provides a graphical programming environment for model generation and simulation execution.

The following section gives a brief overview of the original version of the "Modular Environment for Life Support Systems Simulation and Analysis" (MELISSA, [10]) that served as a basis for the newly developed software tool. The subsequent sections describe how MELISSA V.1 was upgraded to provide synergistic simulation capability. A demonstration of the upgraded tool through an application example is also presented.

BASIC SIMULATION TOOL

The MELISSA simulation environment, as described in [10], uses the graphical programming and user interfaces provided by the base software LabVIEW [7]. MELISSA in its original version (MELISSA V.1) provides several libraries with ECLSS- and EPS- (Electrical Power Supply System) specific components (Table 1), which are implemented as modular subroutines.

Default performance data for all MELISSA modules is taken from literature ([4], [8], [13], [15], [16]), but users can easily adapt the predefined modules to include

Library	Predefined Components
ECLSS	Vapor Compression Distillation, Multifiltration, Four-Bed Molecular Sieve, Sabatier Reactor, Trace Contaminant Control, Condensing Heat Exchanger, Electrolyzer, Crew, Cabin, Tanks for Liquids and Gases, Vent, Air Analyzer
EPS	Energy Storage, Photovoltaic Arrays, Shunt, Eclipse Simulation
Simulation	Simulation Control, Time Control, Datalogging

Table 1: Main Components Provided by MELISSA V.1

customized data, or increase the modeling depth of modules.

Subsystem modules are inserted into the simulation model using a drag-and-drop approach. Linking modules with virtual wires defines the data flow between them, which mirrors the species flows in the real-world system. Due to the graphical programming environment, no further programming is needed. All information required to perform simulation runs is contained in the graphical model (cf. Figure 4), which at the same time is the executable code.

The simulation is based on numeric iteration. For each simulation step, individual modules perform calculations on the species flows they receive. The transition from species flows to species amounts is done only where needed, i.e. in species tanks; simple time-discrete integration is used there [10].

During run-time, the simulation can be controlled by the user through interactive elements. For simulation-specific tasks, like writing simulation and system state data to a file or controlling the time-step used in the simulation, MELISSA service subroutines are provided.

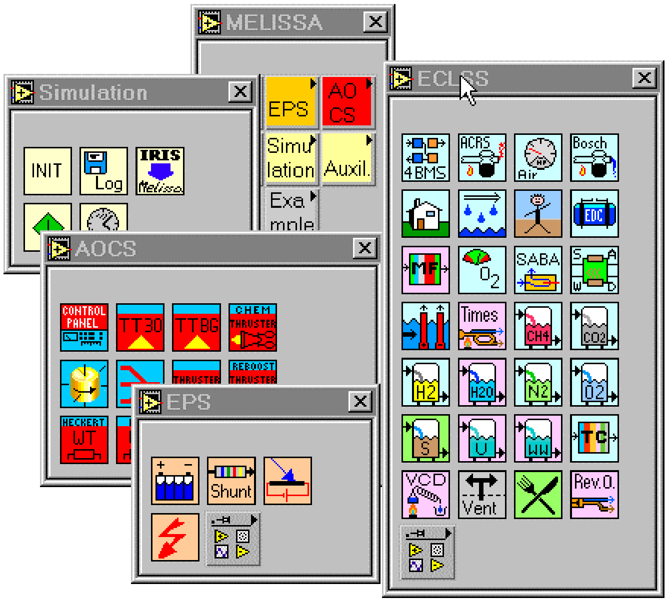


Figure 1: MELISSA V.2 Subsystem and Simulation Module Menus

Library	Predefined Components
ECLSS	Solid Amine Water Desorption, Food Supply, Thermoelectric Integrated Membrane Evaporation System, Reverse Osmosis, Carbon Formation Units, Electrochemically Depolarized CO_2 Concentrator
AOCS	Control Momentum Gyros, Resistojet Thrusters, Arcjet Thrusters, Chemical Propulsion Thrusters, Propellant Tank, AOCS Control
EPS	Preconfigured Power Supply
Simulation	AOCS Simulation Software Interface

Table 2: Additional Main Components Provided by MELISSA V.2

SIMULATION TOOL UPGRADE

MELISSA has been designed from the beginning with an eye on synergistic simulations. Following the addition of predefined AOCS components to the existing ECLSS and EPS libraries, and after incorporating some procedural improvements, this feature can now be put to use. The resulting software is MELISSA V.2, a “Modular Environment for Linked Subsystems Simulation and Analysis”. These upgrades are detailed below.

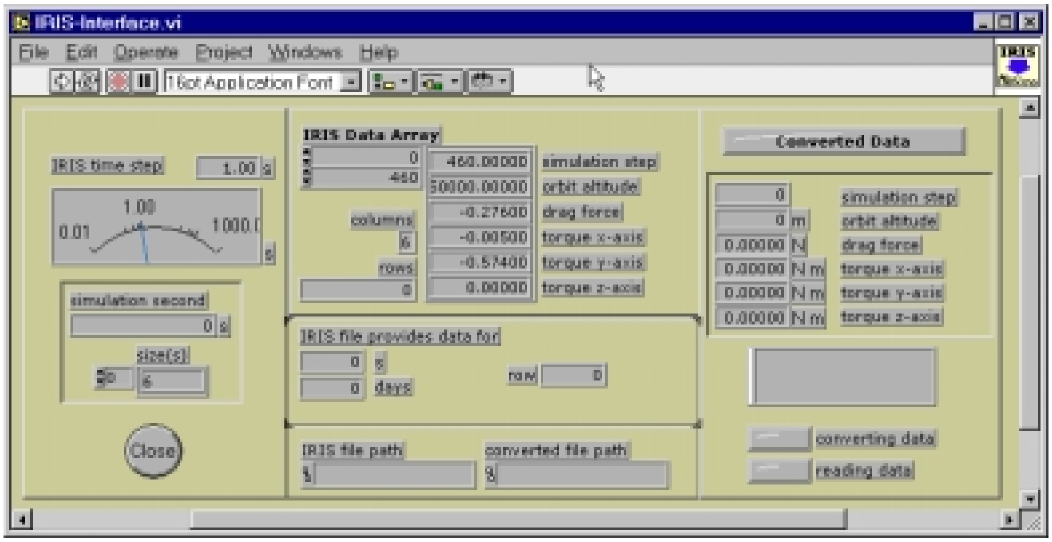
ADDED SYNERGISTIC SIMULATION CAPABILITY

In order to enable MELISSA users to simulate the effects of synergistic linkages between the ECLSS and the AOCS, additional main components listed in Table 2 were made available [11]. On top of subroutines simulating AOCS hardware such as thrusters and Control Momentum Gyros (CMGs), this includes an interface to the attitude and orbit control simulation tool IRIS [1]. IRIS is used in conjunction with MELISSA to provide time-dependent drag and torque data. Figure 2 gives an impression of the interface between the IRIS AOCS simulation and MELISSA.

All modules were modeled based on top-level engineering data taken from literature ([1], [6]) but can be altered to incorporate more detail if required for a specific simulation task.

INCORPORATED USER-FRIENDLY IMPROVEMENTS

In MELISSA V.2, the generation of system models, the execution of simulations, and the general user-friendliness of the software were enhanced. Most improvements were made in accordance with user feedback gathered during the employment of its predecessor version, MELISSA V.1. Users ranged from participants of international workshops on space station design (SSDW, [14]) to graduate students using MELISSA



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-0.00500 torque x-axis
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Figure 2: IRIS/MELISSA Interface for Automated Input of Time-Dependent Orbit and Attitude Data (Altitude, Drag, Torques)

for thesis work. The main changes are outlined in the following.

The most significant modification relates to the simulation approach itself. Each simulation cycle now consists of three sequential steps:

1. Initialization of flow values and other model settings (if required)
2. Simulation calculations (main step)
3. Compilation and logging of simulation state data

This allows for more intuitive system modeling as well as for easier and more transparent data logging. It also gives the user a greater range of possibilities with respect to initialization of the simulation.

Additional changes include the following:

- Simulation accuracy was improved with the rewriting of the generic storage/integration subroutine, on which all tanks and other storage modules are based.
- An automatic check of wire/flow units for consistency accelerates the modeling process and helps the user to avoid mistakes when modeling complex systems.
- A reworked module library concept is provided, along with web-browser-readable Hypertext Markup Language (HTML) documentation of all provided components.

APPLICATION EXAMPLE

To demonstrate a typical case where MELISSA can be applied, an illustrative ECLSS and AOCS was modeled in two different versions, and its respective behavior was simulated over 100 days.

The baseline version contains separate subsystems, the AOCS relying on chemical propulsion thrusters for attitude control (cyclic CMG desaturation) and orbit

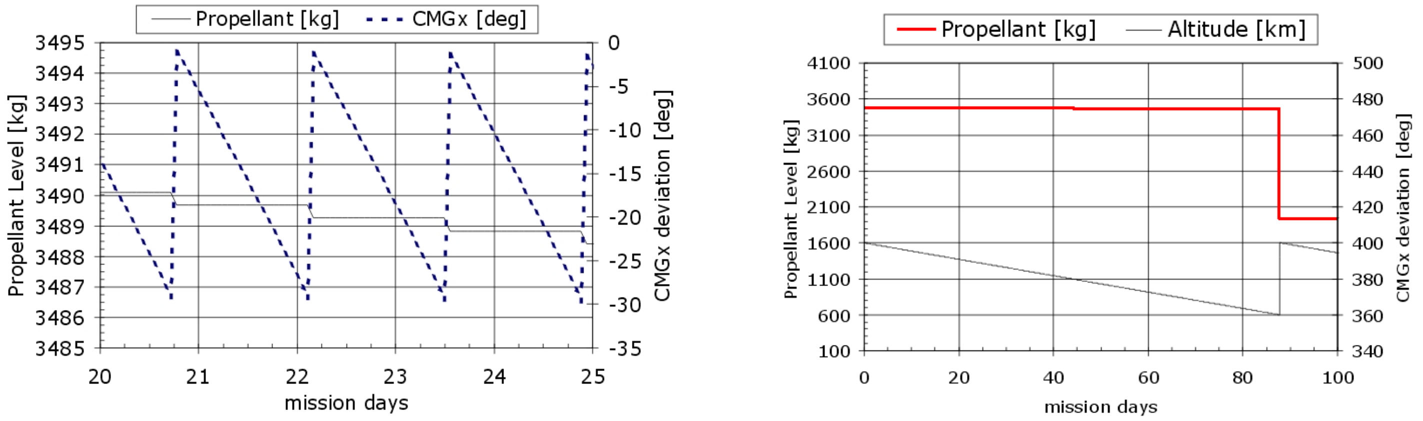

Figure 3: AOCS Simulation Data (Propellant Level, CMG Deviation, Altitude), Baseline System Simulation

	Baseline System	Synergistic System
Wastewater [kg/100d]	+10.9	+86.3
Potable Water [kg/100d]	+190	-2546
AOCS Fuel [kg/100d]	-1552	N/A
Multifiltration Cartridges [kg/100d]	-100	N/A
Average Power Used [W]	14	1218
Additional System Requirements	Multifiltration Unit	Increased Power Generation for Resistojet; Increased Potable Water Storage

Table 3: Summary of Production (+) and Consumption (-) Data for a 100-day Resupply Cycle

introduces resistojets for AOCS purposes (permanent thrust/constant reboost strategy) that use wastewater from the life support system, therefore introducing a synergistic link between AOCS and ECLSS. Constant values for station drag and disturbance torques are used in both cases.

The ECLSS parts of the baseline and the alternative system are similar. Both system designs feature urine pre-treatment by Vapor Compressed Distillation (VCD). In the baseline system, a multifiltration unit is used for wastewater recycling. The air loop is non-regenerative for this simple example. Water vapor is removed from the air; otherwise, adequate air supply is assumed. Figure 4 shows the MELISSA model of the synergistic system.

DISCUSSION OF SIMULATION RESULTS

For the baseline system simulation run, Figure 3 (left) shows the expected periodic deviations of the Control Momentum Gyros, and the associated synchronous drops in propellant level, as the chemical thrusters are used to desaturate the gyros. Figure 3 (right) shows the declining altitude and the reboost at 360km, with an associated massive use of propellant. Table 3 summarizes the rates at which main species were utilized or produced. The slight increase in wastewater is due to the near-complete closure of the water loop. The observed increase in potable water can be traced to the modeling of the crew module, which has “hydrated food” as an input; a remodeling of the crew (being the main mass flow source/sink) is planned that will include a clear separation of food and water flows. Total resupply mass for the subsystems under analysis (AOCS fuel + Multifiltration beds) equals 1652 kg per 100-day resupply cycle.

For the simulation of the synergistic system, Figure 5 shows the same CMG oscillations as those shown for the baseline simulation. Instead of AOCS propellant, wastewater is used for CMG desaturation; the figure shows the expected drops in wastewater level for each CMG desaturation event. The mass flow budget from Table 3 shows increased consumption of water (due to the lack of wastewater regeneration) and increased power generation and water storage requirements. Total resupply mass for the subsystems under analysis (i.e. water resupply only) equals 2546 kg per 100 d.

When comparing simulation results for both system designs, the synergistic alternative has the disadvantage of requiring significantly higher resupply mass; mainly due to the lower specific impulse (I_sp) of water as compared to chemical propellant. At the same time, it presents several advantages in the operational field:

- Hazardous AOCS fuel is removed from the logistics system; only potable water needs to be provided; on the other hand, operation of a water-using resistojet presents a technology/development risk, and provides lower I_sp.
- Microgravity quality of the space station is improved due to constant drag compensation; on the other hand, this strategy requires a suitable x-thruster mounting location that permits aligning of the thruster axis with the station’s center of gravity.
- Due to the large amount of potable water stored, the crew does not have to rely on a functioning water recycling system, thus improving the handling of contingencies.

To help the designer decide on which strategy to use, simulation of other alternative designs, or the employment of additional static assessment techniques such as ESM estimations ([3], [8]), would be indicated.

CONCLUSION

An interactive modeling and simulation tool for life support systems was upgraded to allow for the simultaneous simulation of ECLSS and AOCS. This enables the conceptual design engineer to assess the potential of synergistic couplings between those subsystems.

To demonstrate the functionality of the new tool, a synergistic ECLSS/AOCS design was modeled, simulated, and compared to a non-synergistic baseline system. Modeling and simulations were executed successfully. Simulation results show that the systems under analysis operate as expected.

Further development of the simulation tool will improve the modeling of the crew element, provide batch-processing mode for some ECLSS units, and add more AOCS and ECLSS modules.

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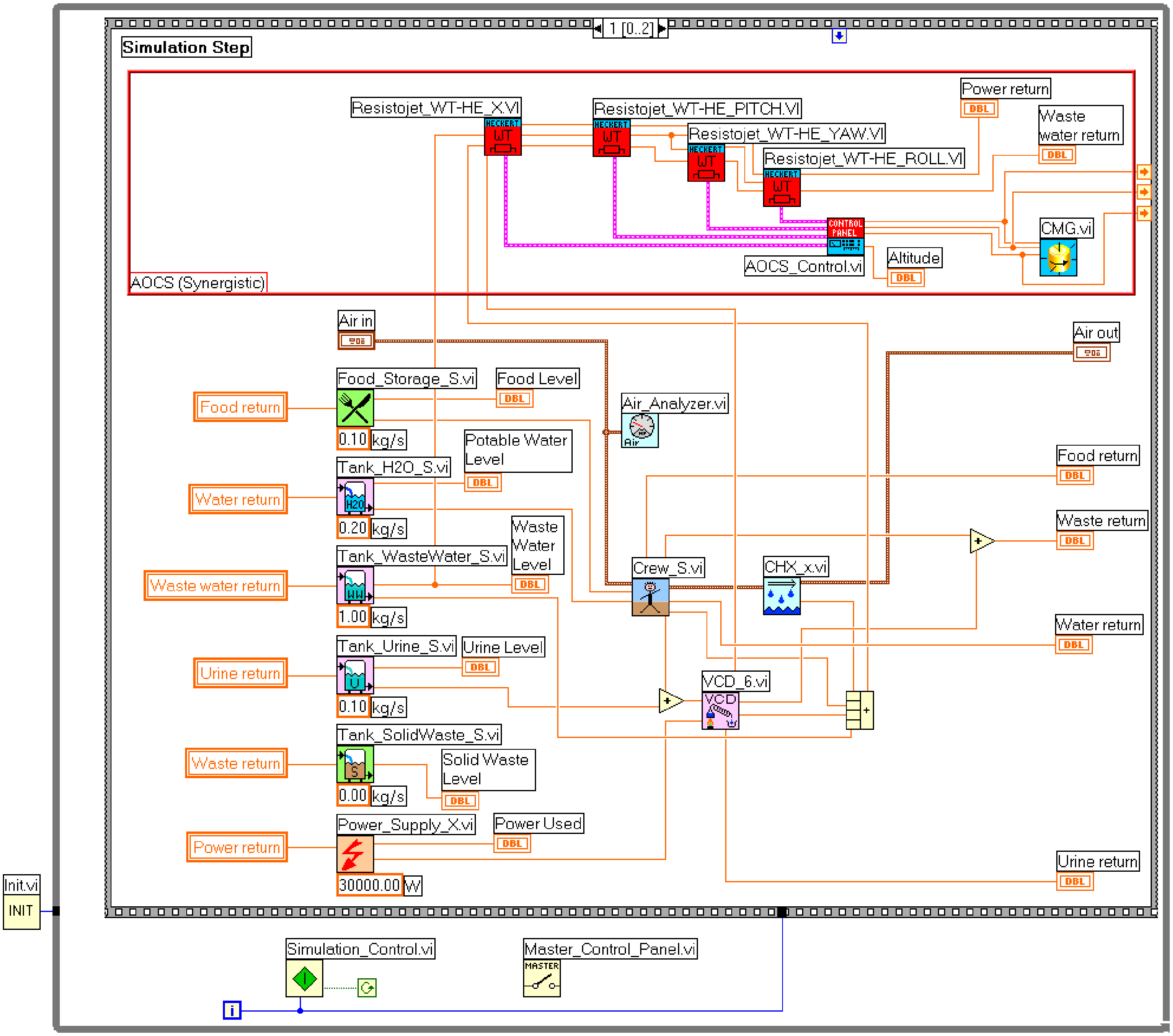

Figure 4: MELISSA Simulation Diagram of Synergistic AOCS/ECLSS Design

Figure 5: ECLSS/AOCS Simulation Data (Wastewater Level, CMG Deviation), Synergistic System Simulation

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ACRONYMS

AOCS	Attitude and Orbit Control System
CMG	Control Momentum Gyro
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Research Center)
ECLSS	Environmental Control and Life Support System
EPS	Electrical Power Supply System
HTML	Hypertext Markup Language
I_sp	Specific Impulse
ISS	International Space Station
MELISSA	Modular Environment for Linked Subsystems Simulation and Analysis
SSDW	Space Station Design Workshop
VCD	Vapor Compressed Distillation