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Hierarchical Control of Space Closed Ecosystems – Expanding Microgrid Concepts to Bioastronautics

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One of the main challenges of human space exploration is the development of artificial ecosystems, which can be used as Life Support Systems (LSSs) to enable long duration human space missions. In an open LSS, no food generation or waste treatment is provided in space and supply from earth is necessary. According to Fig. 1, considering the approximate metabolic consumables and hygiene water, as well as the number of crewmembers [1], a huge mass would be required to be transported from earth, which brings the necessity of a regenerative or closed LSS [2], [3], [4]. Closed ecological systems (CESs) are ecosystems without any matter exchange with outside environment [2]. The most advanced human-made CESs include ALSSTB[1], Biosphere 2[2], BIOS 3[3] (no longer operative), CEEF complex[4], MELiSSA Pilot Plant (MPP)[5], and Concordia Antarctica Station, which are different from one to another with respect to their complexity, size, and degree of closure [2]. CESs are necessary for long-term manned space missions, which aims minimizing support from Earth. They are composed of several specific compartments that together reproduce the main functionalities of an ecological system in continuous mode of operation and under controlled conditions.

Fig. 1. Human consumables and throughput values in kg/crewmember/day

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[2] Oracle, Arizona, US.
[3] Krasnoyarsk, Russia.
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Fig. 2 represents an illustration of one of the leading CESs named MELiSSA (Micro-Ecological Life Support System Alternative), which is composed of six microbiological compartments. As illustrated in Fig. 2, these compartments are connected to each other through gas, liquid, and solid interfaces and each of them has a specific role in the overall process [5], [6], [7]. The main objectives of CESs are to regenerate the atmosphere, to provide and recycle water, to supply the required amount of food to sustain human life, and to process the waste generated in the loop to provide self-sustainability. To this end, individual compartments must be efficiently integrated to close the loop and serve as a regenerative LSS. A significant concern in integrating the complete compartments and developing a closed operational loop is related to designing an efficient, reliable, and dynamic control system that can fulfill system's requirements and guarantee its long-term performance.

From a systemic view point, CESs are autonomous systems integrating various generation, recycling, and consumption subsystems with the storing capability to solve potential unbalance of key elements in the loop. Accordingly, a CES share many similarities with other autonomous systems like islanded microgrids (MGs), which opens up new opportunities to benefit from the recent advances in modelling and control of such complex structures. In this regard, this study aims at exploring the similarities of the islanded MGs with CESs and benefit from MGs highly developed control structures to cope with the complex control tasks of closed ecosystems.

CESs: State of the art

The Russian project BIOS-3 represents one of the first closed ecosystem experiments relying both on microalgae and higher plant crops to convert the CO_2 released by the crew into O_2 with a negligible leak and a degree of closure of 100% for O_2, 85% water, 40% nitrogen, and 20 % minerals [3]. Most of the successful results of BIOS-3 inspired Biosphere-2, which is the biggest closed ecosystem facility ever focused on study human-environment relationships to be used for future outer space habitat designs. It contained aquatic and terrestrial ecosystems colonized with model organisms mimicking the Earth, being a totally sealed environment and just using external energy from the sun. Biosphere-2 experiments in 1991 proved the importance and challenge of the controllability of closed ecosystems, as microorganisms in the soil grew released CO_2 into the atmosphere in an uncontrolled way, thus exceeding the capacity of plants to revitalize the air, while making the atmosphere unbreathable for the crew. Hence, the expected degree of closure of 100 % could not be guaranteed by controllability and leakage issues [8].

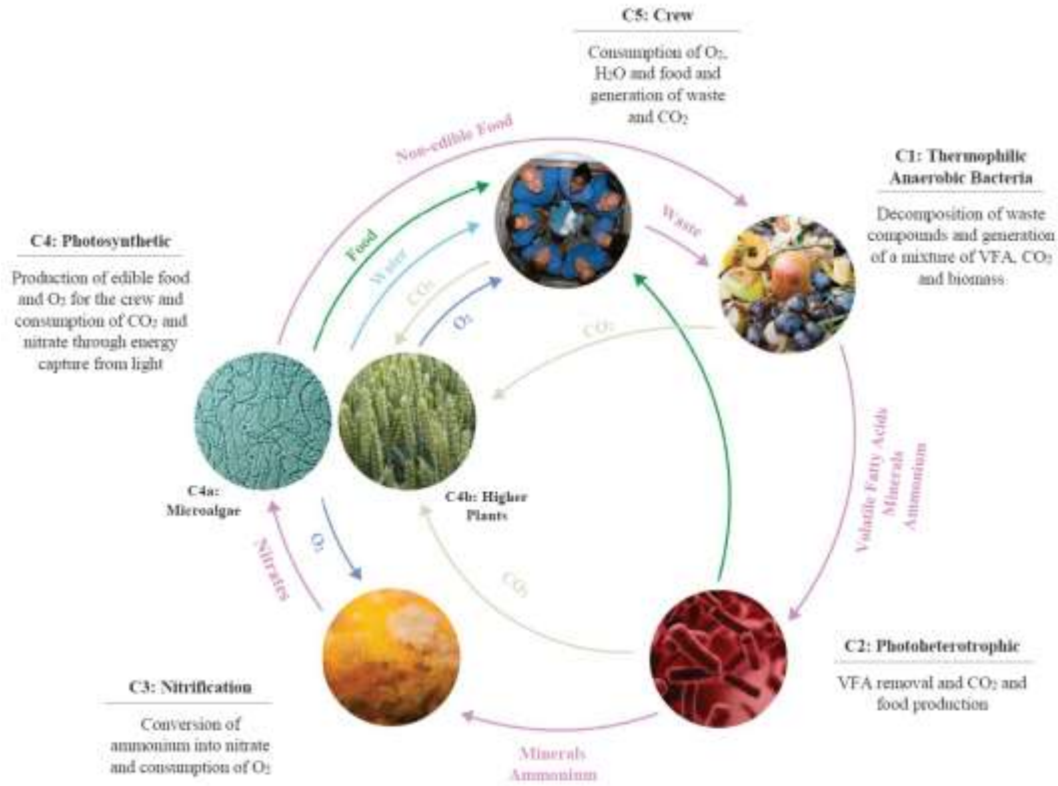

Fig. 2. Illustration of a CES: MELiSSA

One of the longest runs of a closed LSS was promoted by NASA in 1998 named Lunar-Mars Life Support Test, which involved the air revitalisation coupled to food supply from crop culture and waste processing in a 90-day test. One of the outcomes of this project was to boost an integrated control system design to take into account the overall operation to reduce crew and ground personnel intervention time [9].

The recent promising integration results in the MPP connecting the gas phase of the crew chamber and the cyanobacteria bioreactor through a cascade controller serve as a platform to build an advanced control structure for the entire loop [6]. Table 1 gives an overview of the most advanced projects for space applications pointing out their differences in waste management strategies and photosynthetic organisms used.

Table 1 CESs projects: Main technologies for waste management, photosynthetic reactions, and developer.

Project	Waste Management	Photosynthesis	Developer
BIOS-3	Incineration	Microalgae and plant crops	Institute of Biophysics, Russia [3]
Biosphere 2	Biological conversion	Microorganisms consortium, coral reef, tropical rainforest	University of Arizona [8]
CEEF	Incineration	Plant crops	Institute for Environmental Sciences, Japan [10]
ALSSTB	Biological and physical-chemical conversion	Plant crops	NASA [9]
MELiSSA	Biological conversion	Cyanobacteria and plant crops	ESA [7]

From a control viewpoint, previous attempts to close an ecological system reported the importance of controllability in such complex systems. Even though there are different CESs strategies with advanced control structures, to the best of our knowledge there are not any hierarchical control structures (HCS) designed for the integrated operation management of CESs. Only in [5], a HCS concerning the control of the biomass production in one of the compartments of the MPP through adjusting the light intensity is developed, but not extended to more compartments of the loop. Hence, this study will be focused on proposing a hierarchical control framework for CESs including several generation, consumption, and storage subsystems aiming at serving as a regenerative LSS based on the advanced HCS of MGs.

From MGs to CESs

MGs are known as local aggregation of distributed energy resources (DERs), energy storage systems (ESSs), and loads with the capability of operating in either grid-connected or islanded modes [11]. Islanded MGs, MGs without power exchange with the main grid or adjacent MGs, have been implemented in many applications including geographical islands, rural areas, automotive, avionic, and marine industries [12]. The main characteristics of an islanded MG include: The capability of locally solving energy balance problem; Performing several multi-time scale control tasks allied with different operational and technical requirements in system-level as well as component-level; Scheduling several micro-generation units characterizing different dynamical behavior; Supplying MG consumers with the reliable, clean, and sustainable energy taking into account the uncertainty involved in the generated and demanded power; and managing storage possibilities to cope with energy balance and enhance system reliability and performance. MGs are beneficial for both the main grid and MGs users. From the viewpoint of the main grid, a MG is regarded as a controllable entity, which can support the upstream network through providing ancillary services while from the MGs participants' point of view it can be seen as a highly reliable source of power, which can enhance the quality of life of its participants.

On the other hand, CESs represent a small-scale islanded system that aim to distribute matter through the loop in the form of mass flow. Hence, system's operation requires coordination between the energy resources, namely photosynthetic compartments that receive solar energy and convert it into chemical energy, matter-storing systems (MSSs), and matter sinks represented by different compartments including the crew compartment in the system.

Distributed Energy Resources: DERs in MGs include small on-site generation units called micro-sources such as diesel generators, micro turbines, wind turbines, photovoltaic (PV) systems, and so on, which in comparison with conventional power generation systems enhance the reliability of the energy systems while reducing investments costs [13]. DERs in CESs are more limited due to the poor environment in terms of resources found in space. However, sunlight is the most abundant energy source on the Earth and outer Space and plays a crucial role in both renewable-based MGs and CESs. PV systems and photosynthetic complex harness the sunlight energy to produce electrical and chemical potential energy respectively. Although differences in the way of operation, the final product (electrical energy in PVs and energy carrier molecules in photosynthetic cells), and energy conversion efficiency, it is already known that they share many similarities [14], [15]. In a PV cell, the sunlight photon is absorbed by the semiconductor material (e.g. silicon) and results in generating an electron-hole pair. The energized electrons flow through the conductor as electrical current and the resulting electrical output power can be used immediately or stored for later usage. In natural photosynthesis, energy of the absorbed photon results in an excited state of chlorophyll. These high-energy electrons are used to produce the energy storing molecules NADPH and ATP in a series of light-driven reactions. The H_2O molecule as a donor of electron is broken and O_2 is produced as an important byproduct [15], [16]. Fig. 3 represents an illustration of both processes. It is worth mentioning that in CESs, it is not only important to be able to capture solar energy and distribute electrical energy, but to achieve high efficiencies in the conversion of electrical energy to chemical potential.

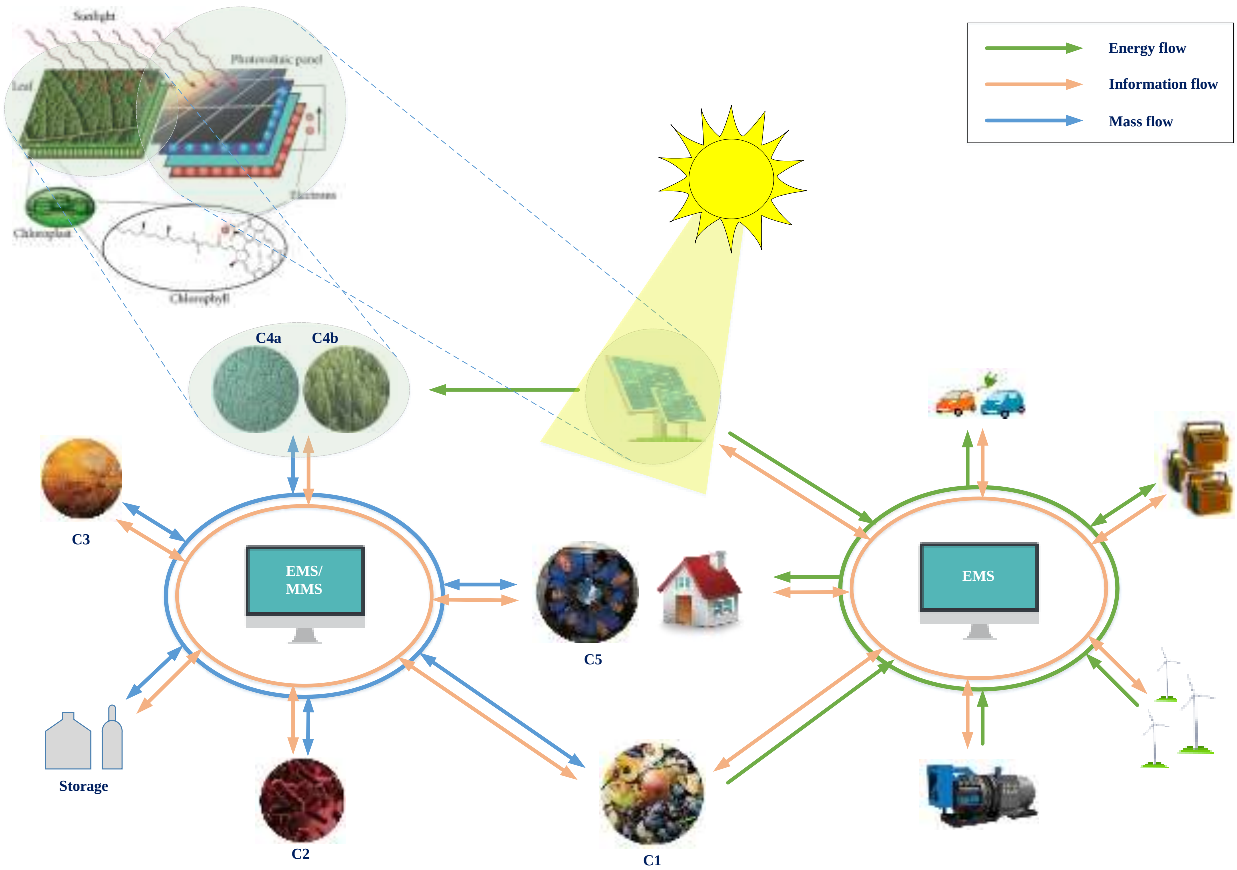

Fig. 3. Illustration of the comparison of MGs and CESs.

Similar to biogas generation technology in MGs, which can provide heat and energy cogeneration, CESs might also include an anaerobic digester to process the generated waste and produce CO_2 [17]. Analogous to micro-generation units in MGs, operational constraints such as minimum uptime/downtime limitations, ramp-rate constraints, and mass flow generation capacity are required to be respected in the control of CESs. As an example, the optimal higher plants growth rate in C4b in MPP (see Fig. 2) is strongly conditioned by its activation time, which is related to the plants circadian rhythm [18], being the 16-hour day-light time when the maximum plants growth rate takes place in the current operational conditions used in the MPP. The minimum deactivation time of this compartment is also required to be longer than 8 hours for a proper functioning of the plants metabolism.

Energy and Mass Storing Systems: Storing systems are essential elements in both MGs and CESs. They can increase system's reliability and flexibility through providing the system with a backup source of energy and the capability of shifting energy production and consumption intervals. In MGs, uncertain nature of the power produced by renewable energy sources (RESs), asynchrony between the peak interval of power generation and consumption, as well as the different dynamical responses of various elements are among the main motivations of incorporating ESSs. In this sense, ESS management is a significant control task in the renewable-based MGs [19], [20]. In CESs, due to the day-night cycles of the plants and different dynamics of the loop elements, storage systems are used for buffering purposes. Increasing the cells or plant population, results in producing more O_2, water, and food, which can be stored for later consumption.

However, it is important to optimize the size of storing tanks to keep the system weight at its minimum, a requirement stated by ESA's ALISSE criteria [21], which is also a main concern in isolated mobile MGs such as ships and space MGs. Besides, considering technical issues such as accumulation limitations and technical constraints of storage tanks (e.g. flow rate limitations, minimum and maximum storing capacity, etc.), including the MSSs will complicate the CES control process.

Hybridization is another efficient way to cope with different dynamics of the system components and benefit from advances in different technologies. As an example, in a hybrid MG including fuel cell, battery, and ultra-capacitors, the dynamic response of the system to power demand variations can be improved by utilizing the stored energy. This concept can be also applied to CESs where the two photosynthetic compartments based on cyanobacteria and higher plants feature different dynamic response characteristics. Besides, stored materials can be used to respond to sudden changes in the system.

Energy/Mass Consumers: In a CES, the crew consumption rate drives the entire operating loop. Survival of the crew is required to be ensured through satisfying specific conditions for the availability of water, food, and gas concentration. Similar to MGs, the consumers are considered one of the main source of uncertainty besides the sunlight as their activities can considerably affect the supply of matter. Although we can have an estimate of the average O_2 consumption rate of the whole loop, many factors can affect this rate like the crew activity, the elemental composition of feces and urine and the consumption and generation rates of microbial communities.

MGs should be able to operate autonomously and interact with other MGs and the main grid while the state of the art of LSSs are still not in a developed-enough stage to consider inter-connections between different CESs. In both MGs and CESs, DERs and ESSs/MSSs spread over the system and are connected to each other and loads.

Like in MGs, the design and planning of a CES is an important field of study, which needs to take into account different considerations such as the system scale, the degree of closure (variable accounting for the degree of internal regeneration), the efficiency of individual compartments and the whole system, the safety and the weight of the system. All the considerations affecting the design and operation of a CES are well described in the ALISSE criteria [21], which is out of the scope of this study. This research is mainly focused on the control and operation management of CESs.

Although there are striking similarities between both systems, some of the specific characteristics of CESs make their design and operation more challenging than renewable-based MGs. As an example, despite light, which comes from an external source of energy, other energy sources are generated inside the loop. Hence, the generation capacity of different matter resources cannot be predetermined and are specified based on the current state of the dynamic system. However, the existing similarities offer the possibility to use the advanced control methodologies developed for MGs to CESs, an aerospace application of increasing interest.

Control and Operation Managements of CESs

According to Fig. 2, the integrated system of a CES contains both the dynamics of the individual compartments as well as the interacting parts. The integrated system is very complex with a large number of state and manipulated variables, non-linear interacting dynamics, and several varying operational and technical limitations. Besides, the dynamic response time of the processes in the various compartments are noticeably different. The impact of the dynamics of the different phenomena that takes place in each compartment in the whole loop is strongly affected by both the volume, the residence time, and the nominal concentration of the compounds in each compartment.

The multi-objective control process requires meeting mainly two control objectives, namely balancing the consumption and production of oxygen, water, and food to guarantee life support, and to process the loop wastes to achieve high levels of recycling.

Due to the multiple time scales of the CESs and different time resolutions of the objectives, an integrated control structure may not be successful. The combination of the need of a long prediction horizon, in the order of several weeks, with short control time steps, in the order of a few minutes or seconds, results in a high-dimension control problem, which cannot be handled in real-time. Hence, a multi-time frame organization of the controller is required.

Furthermore, developing appropriate models to be used in different layers and sub-layers of the control hierarchy with different levels of abstraction is of vital importance. While non-linear mechanistic models provide a good representation of the real process behavior, they should be adapted for control purposes with small time resolution. Hence, developed models should provide a satisfactory compromise between the accuracy in their operating range and complexity.

Hierarchical Control of MGs: To accommodate different time scales, MGs control is organized in a HCS [22], [23]. The significant objectives of MG mission including voltage and frequency regulation, power sharing, synchronization, resilient and economic operation, feature different time scales in the range of milliseconds to several days [24]. There exist several standards related to MGs operation and control including IEC 62898-1, IEC/TS 62898-2, IEC 62898-3-1, and IEEE standard 2030.7-2017 [25]-[28]. ANSI/ISA-95 or ISA-95 is an international standard for automation system design and implementation for enterprise-control system integration in all industries, which is general-enough to be applied in chemical processes. In a HCS based on ISA-95, the control tasks are distributed in several levels following a functional and temporal decomposition. The standard multi-level HCS based on ISA-95 and its adaptation to the control strategy of MGs is represented in Fig. 4 [23].

In this scheme, the control levels are different from each other concerning the functionality, the speed of response, and the operation period as well as communication requirements [29]. Besides, the complexity of the required models differs in different layers. In a HCS, different control levels are interacting with each other by adjusting reference trajectories and constraints boundaries. To preserve stability and robust performance of the system, time-frame management of the reference signals and control commands of one level to the lower levels is of vital importance. Hence, the bandwidth is decreased with the increase of the control levels.

Expanding the HCS of MGs to control CESs: The parallelisms between CESs and isolated MGs show the great potential of benefiting from the highly developed HCS of the islanded MGs to cope with the complex control tasks of CESs. Accordingly, hierarchical control for operation management of MGs is planned to be adapted for controlling the CESs in this study. Organizing the control strategy in several layers is also consistent with the variety of the control tasks and the different time scales of CESs. The significance of adopting a generic system model approach containing several layers is represented in [5] for different purposes of control, management, test, and optimization.

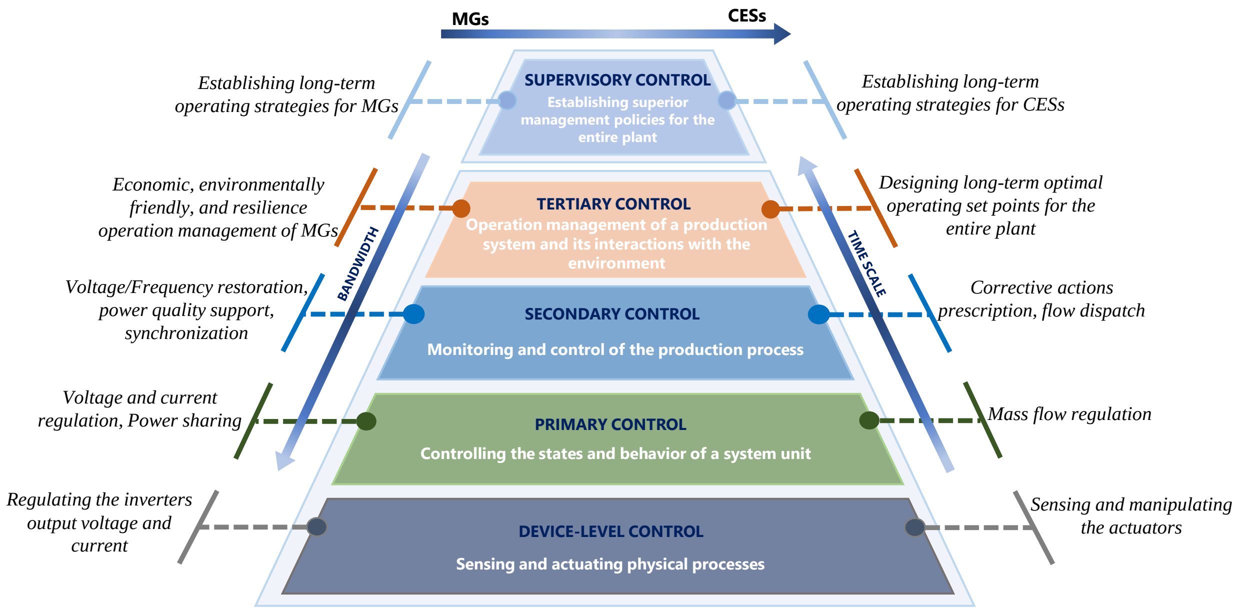

Fig. 4. Multi-level hierarchical control structure of MGs and CESs

Adopting the HCS of MGs, to deal with the complexity of the optimization and control of the entire loop of a CES, the control process of the integrated system can be distributed in several levels as follows. The adaptation of the HCS of MGs to CESs is also outlined in Fig. 4, according to the following levels:

Level 0 (Device-level control): The controllers at this level are responsible for sensing and manipulating the actuators of the biochemical process to regulate the behavior of the associated compartment following control command signals.

Level 1 (Primary control): At this level, a local controller is responsible for devising appropriate control actions to follow the mass flow references received from the higher-level controllers. Besides, control agents at this level are responsible of sharing information about the dynamic compartment constraints so the higher-level controllers can have a global view of the whole process to optimally distribute resources [30]. The strong coupling of variables and the interdependency of compartments may require the dynamically adjustment of the constraints.

Level 2 (Secondary control): To compensate for the set points deviations and to improve the tracking performance of the primary controllers, a secondary controller is required to provide local controllers with corrective actions. The corrective actions are obtained based on the feedback signals and the desired operating references and sent to the local controllers. To preserve stability of the system, the secondary controller is required to be faster than the tertiary control but slower than the primary controllers.

Level 3 (Tertiary control): The responsibility of this level is to guarantee long-term performance of the process and provide optimal operating set points based on the predicted evolution of the demand and supply of matter by different compartments while taking into account their dynamic operating constraints and technical limitations. In case matter exchange between different ecosystems is desired, the flow management can be also scheduled at this level.

Level 4 (Supervisory control): Supervisory controller is devoted to establish the operating strategies of the system following a set of main criteria such as ESA's ALISSE criteria [21]. Monitoring the state of health (SoH) of the system and projecting its states in the future using high-fidelity models and simulating the system in a faster than reality environment, the supervisory controller will be able to support reliable operation of the system through adjusting its operating strategies and predictive maintenance.

Accommodating the multiple time scale of the system, a temporal decomposition is also required at some levels [31], [32]. As a result, the control levels might consist of several sublayers, which act on different time scales while handling the corresponding objective function and relevant constraints. The number of sublayers and associated prediction and control horizons, as well as the required sampling rate are determined based on the time scale properties of the system and the desired control tasks. Besides, the interactions between different layers and sublayers are required to be clearly defined to consider the functionality of a sublayer in determining reference trajectories or adjusting the constraints of other sublayers [32]. By applying the proposed HCS, different subsystems are integrated and the system operation can be controlled in a coordinated manner. Fig. 5 illustrates the proposed HCS for an exemplary pilot plant (MPP).

Control Methodology: In the HCS for CESs, appropriate control methods are developed at each level considering the control requirements (such as control functionality or speed of controller response) and system characteristics among others. The capability of model predictive control (MPC) in considering system constraints and taking into account future predictions of the system behavior as well as its closed-loop control approximation makes it a good candidate for deriving the control strategy in the higher control levels, specifically tertiary and secondary levels. While at the lower levels, faster controllers such as PI, PID or predictive functional control (PFC) are highly preferred. PFC is a variant of MPC, which is characterized by its simple calculation algorithm and easy implementation. Using the two main characteristics of coincidence point (*h* steps later than the current step where the reference trajectory and the predicted process output will coincide) and basic functions distinguishes the PFC method from other predictive controllers [33]. In the proposed control structure, MPC is used at tertiary and secondary levels while PFC is deployed for controlling the light intensity in compartment C4a and the input gas flow in C3.

Prediction system and data exchange: To implement the HCS, the required information (state of the system, system parameters, prediction of disturbances, updated trajectories, constraints boundaries, etc.) at each control level and sub-level should be provided.

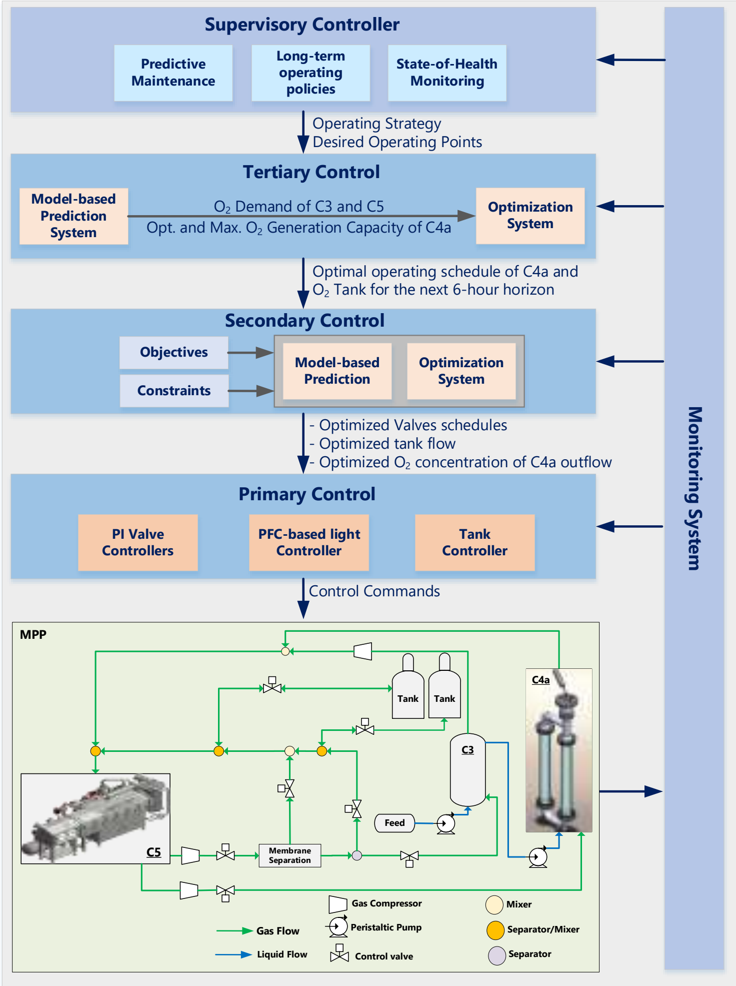

Fig. 5. Hierarchical control strategy for oxygen management

Data gathering is conducted through reliable monitoring systems and relevant information is exchanged with the controllers through designated communication systems. Advanced estimation and prediction methods are required to find the latest values of the unmeasurable state variables and system dynamics evolution during the prediction horizon. The estimation and prediction methodologies should be fast-enough for online implementation. In this study, a model-based prediction system is deployed at the tertiary level using the high-fidelity models of the pilot plant and the data obtained through the monitoring system.

Simulation Analysis

In this Section, the performance of the proposed HCS will be evaluated using the MPP as a test case. The MPP was built in 2009 to integrate the individual compartments to have a complete operational loop in a testing facility with high quality standards. The demonstration scenario of the MPP is to achieve a closed liquid and gas loop fulfilling 100% of O_2 requirements and at least 20% of food requirements for 1 person. Fig. 6 illustrates four compartments of the MPP.

(a) (b) (c) (d)

Fig. 6. MELiSSA Pilot Plant (a) Compartment C3, (b) Compartment C4a, (c) Compartment C4b, (d) Compartment C5.

Simulation analyses are based on a 25-day simulation period implemented in the MATLAB environment using the proposed HCS for the aggregation of three compartments and a gas storing system as shown in Fig. 5 and the nominal operating conditions used in the MPP [6]. The goal is to assess the long-term operation of the MPP using the proposed HCS with an O_2 reference of 21% in the crew compartment.

The prediction horizon of the MPC at the tertiary and secondary levels are set to 6 and 1 hours respectively, while the sampling time of the controller are equal to 1h, 6 min, and 36 sec for the controllers at tertiary, secondary, and primary levels, respectively. According to the simulation results represented in Fig. 7, the dynamics of the crew compartment correspond to a circadian rhythm of high O_2 consumption during the day and low O_2 consumption during the night (Fig. 7a). The secondary control is responsible for maintaining the O_2 concentration in the crew compartment within a specified boundary (19% - 24%) while following the references received from the tertiary controller regarding the storage tank charge/discharge rate and the O_2 supply rate of C4a. The scope of the tertiary control is to determine the optimal operating conditions for the plant taking into account the overall predicted O_2 consumption and production rates and certain operating criteria determined by the supervisory control. In the simulation presented, the supervisory control aims to keep the pressure of the storage gas tank around a reference level of 50% of the rated value and to use two nominal levels of light intensity in C4a operation, namely 225 W/m^2 and 84 W/m^2 for day and night shifts, respectively. In Fig. 7b-c it can be observed how the secondary control generates a conciliatory response between the references received from the tertiary level and the boundaries imposed on the O_2 concentration in the crew compartment. At primary control level, the light intensity in C4a fluctuates around the two nominal points for day and night shifts (Fig. 7d) and the O_2 tank pressure level remains close to the reference level (Fig. 7e).

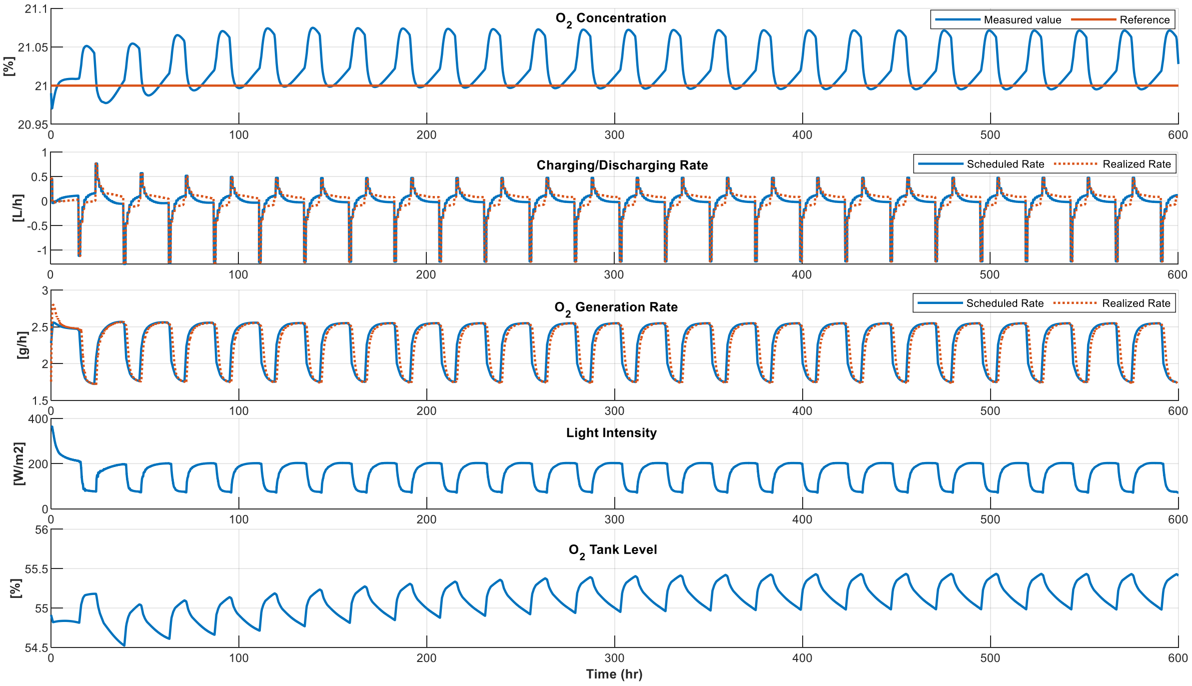

Fig. 7. (a) Concentration of O_2 in the crew compartment; (b) Scheduled storage charging(-)/discharging(+) rate of the storage tank by tertiary control and the realized rate; (c) Scheduled O_2 supply assigned to C4a by tertiary control and the realized rate; d) Light Intensity in C4a determined by C4a Primary controller; (e) O_2 Tank pressure level.

Looking to the Future

Adapting the well-developed hierarchical control strategy of MGs to the control of CESs is a promising approach to deal with their complex control task. In this study, a hierarchical control strategy for CESs was introduced based on the multi-level control structure of MGs pointing out the similarities between both systems. The control structure can be extended for controlling other CESs, not only terrestrial LSSs, but also Mars or Lunar-based LSSs in the future. Besides, the hierarchical structure can be effectively scaled-up to include interconnection of several ecosystems. To design the HCS of CESs, hardware-in-the-loop (HIL) simulation and digital twinning provide unique opportunities, which are explored in the following.

Hardware-In-The-Loop: To validate the controller performance and reduce the implementation risk, HIL simulations can be deployed. Using the HIL simulation, the real-time response of the designed controller to the stimuli from the real plant model can be observed and utilized for evaluating and improving the controller performance in early development stages. It can also be used for validating the developed model of the plant. Taking the advantage of efficient digital platforms, flexible and high performance controllers can be designed for implementing complex control methodologies. In this sense, field programmable gate array (FPGA) is an attractive solution to design a customized digital system, which substantially reduces the execution time of the controller exploiting wide parallelization. Including FPGA in the loop, other control functionalities such as SoH monitoring and predictive maintenance can be implemented during the remaining time from the end of the control task and the next sampling time [34].

Digital twinning: Digital twinning is the virtual representation of a system to mirror the operating conditions of its corresponding twin in the real world. The digital twin (DT) allows the system designers and decision makers to assess the dynamic behavior of the system during the development stages, implementation, operation, and service phases for making well-informed decisions. DT is based on high-fidelity models of the physical system and is connected to the physical counterpart through bi-directional communication links. In this way, the real-time data obtained from the physical system will help improve the accuracy of the DT, while DT can support the optimal control and operation of the physical system through providing an advanced decision-support system and facilitating efficient in-house and remote monitoring. Considering the complexity involved in designing the control system of CESs, DT can provide an unprecedented advanced platform to enhance the controller system performance during the CESs' life time.

Conclusion

Taking into account the recent advances in space exploration knowledge and technologies, and the increasing tendency towards long-term missions on Mars and Moon, developing efficient and reliable LSSs is of vital importance. The design of efficient LSSs necessitates advanced control strategies with the capability of managing a highly complex process.

From a systemic point of view, CESs are autonomous systems integrating various generation, recycling, and consumption subsystems with the storage capability to locally solve potential matter and energy unbalance problems. From this perspective, CESs share striking similarities with isolated MGs developed for solving energy balance problems in an autonomous and independent manner. In this regard, a hierarchical control strategy for CESs was proposed based on the multi-level control structure of the MGs. Supervisory controller at the top of hierarchy decides about the operating policy of the plant through a human-machine interface. Strategical decisions related to operating priorities, predictive maintenance, SoH monitoring, and standard CESs criteria are performed at this level. Tertiary, secondary, and primary controllers at lower levels determine the optimal operating points of the system considering specific requirements and operating goals at different time scales. Simulation results of applying the proposed method to MPP approved the effectiveness of the proposed control structure in achieving a desired performance while meeting the system's technical and operational requirements. Future works are related to enhance the controllers' performance in presence of different kinds of disturbance besides aggregating other compartments in the loop.

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