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A PERSPECTIVE ON CELSS CONTROL ISSUES

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ABSTRACT

Some issues of Controlled Ecological Life Support Systems (CELSS) analysis and design which are effectively addressed from a systems control theoretic perspective are discussed. CELSS system properties which may be elucidated using control theory in conjunction with mathematical and simulation modeling are enumerated. The approach which is being taken to the design of a control strategy for the Crop Growth Research Chamber and the relationship of that approach to CELSS plant growth unit subsystems control is described.

INTRODUCTION

In any life support system, whether it is open, regenerative through strictly physical-chemical processes, or bioregenerative, the primary goal is to provide a support structure for the maintenance of desirable conditions for the humans within the crew compartment. These conditions include the provision of adequate nourishment, potable water, utility water, a suitable thermal environment and properly balanced and pressurized gaseous atmosphere, and the removal of wastes. In the terminology of control theory, the dynamic system whose behavior we desire to influence is called the "plant", which consists, in the context of a life support system, of the crew and their immediate environment. Fig. 1 illustrates the crew compartment as the "plant" with respect to a reference configuration for a Controlled Ecological Life Support System (CELSS). In that bioregenerative system, the remaining portions of the system are the life support system control components. The control concept is realized by considering the dynamics of the plant, the dynamics of the control system components, the behavioral goals of the controlled system and is described in [2] as "the process of influencing the behavior of a dynamical system so as to achieve a desired goal." Through the mathematics of control theory, control laws are derived which the controllable variables of the system must follow in order to achieve desired system behavior.

The Hierarchy of Control Concerns.

Fig. 1 illustrates that a CELSS consists of a complex interconnection of dynamic subsystems, the behavior of each of which may require management by means of control. The hierarchy of control in a CELSS is illustrated in [3]. Several hierarchical levels are present in a CELSS: components, subsystems, and complete CELSS system. The element defined as the "plant" will differ among hierarchical levels as well as among systems on the same hierarchical level. The goals associated with each system may differ, but the aspects of control issues which will be discussed are applicable on each hierarchical level.

Passive and Active Control.

It has been suggested that the CELSS design approach include the property of modularity, i.e. the processors (dynamic components such as plants, waste processor, crew) interact indirectly through mass storage elements.[4] As noted in [4], the mass storages in a CELSS are equivalent to the reservoirs of inorganic material found on Earth. Storages have been demonstrated to be effective buffers in a CELSS, particularly under component failure conditions. Because of the volume and mass requirements, the use of storage in a CELSS is limited. The dynamic behavior of stable systems can be influenced by using storages as passive control devices. If, however, a dynamic system is not stable, feedback (active control) is required to regulate the behavior of the system.

If the system is stable but is subject to disturbances which are not predictable, feedback control may be required to meet desired performance objectives. Implementation of feedback control can reduce the sensitivity a system to a variety of disturbances. Newly emerging perspectives of robust control can produce closed loop systems which are significantly independent of the effects of uncertainties and disturbances. In the following sections, attention is focused on the development of active (feedback), and especially robust, control systems for CELSS.

Development of Control Laws.

Rules for appropriate control actions are mathematical. For feedback control, these rules represent the sequence of signals, functions of the states of the system, which are sent to the control actuator in order to achieve the desired system behavior.

The rules for control actions are based upon both a model of the system and the goals which the behavior of the controlled system must achieve. When the system is similar to one with which the control designer already has some familiarity, initial control law design may be based upon his previous experience (i.e. a mental model) and then tuned to accommodate the unique aspects of the system under consideration. When the system or the performance requirements of the system represents a significant departure from familiar systems, a model which will provide the designer with an organized approach to control law development is required.

A means for analyzing the characteristics and behavior of a dynamic system is provided by a mathematical model.[1] The analysis of these characteristics in conjunction with a mathematical statement of the performance objectives of the controlled system leads directly to a mathematical description of the control laws required for that system-performance combination.

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[1]A distinction is made between mathematical models and other system models such as symbolic or conceptual models, computer or simulation models, physical models or mock ups, etc.

Mathematical Modeling.

The role of mathematics and mathematical modeling in control theory is elegantly developed in [2]. Some particularly relevant passages from that document are excerpted in the following section.

The mathematical modeling issue in control design differs from that in scientific research. The fundamental challenge in control modeling is to find parsimonious representations of complex physical and biophysical phenomena which are adequate for the analytical and computational needs of control design. For scientific understanding, great emphasis is placed on developing microscopically accurate models derived from physical laws. In theory, once such a model is firmly established, the control design based upon it is at least computationally feasible but may be so complex as to be impossible to implement. It may not be possible, however, to write down exact dynamic laws since processes, such as some biophysical responses to the special environments produced in a CELSS, may be poorly understood.

It is well established that feedback reduces the effect of uncertainties including modeling errors. This would imply that, in the extreme, model imperfections are not relevant in the context of control. From such a perspective, what would be needed is a powerful feedback design methodology yielding a robust, fault-tolerant control system. The process of control modeling therefore involves identifying the appropriate mathematical structure - rich enough for adequate problem description yet simple enough for mathematical tractability - and then bringing the power of mathematical machinery to bear on the solution of the control problem.[2]

Mathematical Model Characteristics.

The suitability of the mathematical model for control design is determined by the physical properties of the system and the control objective. The modeler must decide whether the system is best represented in the continuous or discrete time domain, whether distributed phenomena can be suitably represented by lumped models (i.e. the need for partial differential equations versus the adequacy of ordinary differential equations), and whether the nonlinear phenomena in the system must be fully accounted for. Robustness considerations are involved in the selection of the time scale of the model. Fast stable dynamics, which are usually ignored in conventional control analysis, cannot necessarily be neglected in the design of robust controllers. Robustness considerations also arise in selection of the level of aggregation in modeling, particularly with respect to biological phenomena.

Representing Uncertainty.

Uncertainties in the representation of a dynamic system for control design purposes include those related to parameter values, those related to functionality and those related to external disturbances. Uncertainty in parameters may be due to inherent variability in components of a system, variation in characteristics as components age, variations in response rates as environmental conditions change, etc. Uncertainty in functionality may arise from poorly understood processes, from functional variation with life stage or environmental conditions, from unknown but finite higher order dynamics, from failures, etc. Errors in rate functions due to aggregation must be accounted for in the mathematical representation of uncertainty.

Some controller design techniques [5] require at least partial knowledge of the statistics of the uncertainties. Other techniques require knowledge only of the bounds or the uncertainties [6, 7], but conservatism in design is reduced when the effect of uncertainty can be expressed in terms of a frequency content.[7, 8] The control design method selected is influenced by, among other factors, the information available concerning the uncertainties.

Analysis of the System Model.

Many important questions related to the acceptability of performance of a dynamic system can be evaluated by analyzing its mathematical model. In addition, the analysis process provides information about the system which is fundamental to the synthesis of effective control.

Stability.

A fundamental question to be addressed is whether the system is stable. The definition of stability is not unique. [9] In the sense that it is used here, stability is defined with reference to a region of the system space about the desired operating points. A dynamic system is said to be stable to a region if the states of that system, when perturbed from an equilibrium point within that region, remain within that region for all time thereafter.

The fundamental niche of a living system is described by the range of tolerable environmental (i.e. biotic and abiotic) conditions. The organism will survive within the region described by the full range of that niche. If the environmental system is stable to the region of the niche, the organism will survive. Within the region of the fundamental niche lies a subregion in the organism exhibits some desired characteristics and it is within this subregion, defined by performance objectives in addition to basic survival, that we wish to confine the environmental variables. If an environmental system is stable to this subregion, desirable operation of the living system will occur.

The "plant" for a complete CELSS, i.e. the crew compartment with no inputs, is not stable by this definition. In an open life support system, the states of the crew subsystem can be forced to remain within an acceptable region for the duration of the mission by introducing an environmental control system and providing source and sink reservoirs which are sufficiently large. If sources (stores) can be exhausted or sinks (storages) can become saturated, the system fails the criterion for stability as defined. If regular resupply is included as a state dependent input, the stability criterion may be met by the controlled system. In the completely closed CELSS, i.e. with no resupply and no "unusable wastes" (as indicated in Fig. 1), the criterion of stability to an acceptable region must be met. The region of acceptability would be defined as the subregion for desirable operation for normal conditions and as the region of the fundamental niche for failure conditions or other emergency conditions.

Robustness.

Analysis of a mathematical model of a system may indicate that it is stable for nominal values of the parameters. Deviations of the parameters from their nominal values may result in an unstable system. Additionally, disturbances to the system may drive the system states or outputs of interest out of the desired region. Robustness measures can be applied to the mathematical model to determine the stability robustness of the system to the expected variations in parameters.[10]

Stabilizibility and controllability.

If a system is stable to a desired region or subregion under all uncertainties and if no further optimization of performance is needed, no additional control is required. If this is not true, then the available control variables must be employed to attempt to maintain the system states or outputs within the desired region. The mathematical model may be analyzed to determine whether the control variables which are available can be manipulated in any way to maintain regional stability. If and only if all system states can be brought to specified values in finite time by means of the available inputs, the system is said to be controllable. If all unstable modes can be modified by the controls, the system is said to be stabilizable. If it is necessary to maintain a stabilizable system within a region, the available control variables may be sufficient to do so. If it is necessary to bring the stabilizable system to another operating region, a restructuring of the control variables will be required. If the system is not stabilizable with the available control variables, a restructuring of the control variables will be required. This restructuring may involve the addition, relocation or resizing of control variables or a redesign of control actuators. (See [11] and references therein.)

Detectibility and observability.

The outputs of the system which are available for measurement can affect the ability to implement effective control algorithms. The likelihood of implementing an effective control decreases progressively from (a) the situation in which all the system states can be measured, to (b) the case in which not all states can be measured but all the information about the dynamics of the system can be reconstructed from the available measurements, to (c) the situation in which only the stable modes of the system are unobservable through the measurements. The mathematical model of the system may be analyzed to determine which of these cases exists as the system is currently designed. As a result of this analysis, the measurement system may need to be restructured in order to provide the information required for implementation of a control algorithm. This restructuring may involve the addition, relocation or redesign of measurement instruments. (See [11] and references therein.)

Coupling.

The mathematical model can be examined to determine the degree of coupling which the system exhibits among the system variables and the control variables. A lightly coupled system may allow the system to be analyzed as a set of single input single output systems, significantly simplifying the control strategy. Strong coupling will require analysis as a unified multiple input multiple output system, possibly resulting in interrelated control strategies.

Development of Control Algorithms.

As previously noted the development of control algorithms depends upon both the characteristics of the system to be controlled and the performance objective. The objective of a bioregenerative life support system is to provide a self sustaining system for a long duration, in theory indefinitely. The constraints on the deviations of the values of some system variables from some nominal constant or prescribed time dependent reference will be fixed by biological and physical requirements. A CELSS must be at least stable to a region (described by these reference values and deviations) for the design life of the CELSS. This stability must be maintained in the face of parameter variations, external disturbances, and internal functional changes, i.e. any control strategy must be robust to these factors. An analysis of the overall system will assist in determining the performance requirements which this system constraint places upon the subsystems and their components. Such requirements include dynamic response, accuracy, noise sensitivity, control range, etc.

It should be noted that a robust control strategy is not necessarily unique. It is possible that such a strategy could be arrived at by developing an algorithm by some other means. However, without a formal procedure which incorporates establishing robustness as a required property of the design, it is difficult to demonstrate with confidence that robustness has actually been achieved. Whatever control strategies are developed, the hierarchy of control algorithms for subsystems and components should, collectively, not impose excessive requirements for computational intensity and should be numerically well conditioned.

Intelligent Control.

Intelligent control represents the integration of symbolic computation, numeric computation and artificial intelligence

(AI). AI may play an important role in decisions concerning which control strategy to use in view of changes in the control environment. The selection of the most appropriate control strategy for physical systems has been based upon analysis of a system model provided to the AI system using searches for best matches to dynamic response patterns [12]. It is possible that the relationship between biological age and chronological age of a crop in an operational CELSS may differ from the relationship established in previous studies. Because of this potential discrepancy and the fact that control strategies (e.g. harvesting) are related to biological age, it may be necessary to monitor the biological age of a crop using techniques such as image processing in combination with measurements of dynamic biophysical responses. An AI system such as that reported in [12] might be used to search for model matches. Depending upon the best match selected, the most appropriate environmental control strategy for a crop of that particular biological age could be employed to maintain, accelerate or decelerate growth and development as required. The use of this level of response for intelligent autonomous systems is discussed in [13].

Simulation Modeling.

Simulation models are valuable tools for demonstrating and testing the performance of systems. Scenario studies can be conducted to verify the effectiveness of the control design. Recall that it is characteristic of the system control problem to employ simplified models for the purpose of controller synthesis. These models typically (a) employ functionally more simple representations of process behavior and (b) do not describe all stable dynamics. Computer simulations, based on more comprehensive and nearly complete models which include at least the most significant nonlinearities, can be utilized to demonstrate controlled system performance.

Important properties of simulation models are portability and modularity. Portability of a model to various computers with little modification enhances communication among researchers and makes models more readily adapted to state-of-the-art developments in computer hardware. Modular design of modeling software allows system design option variations to be examined easily without significantly affecting the programming code of the remainder of the model.

Many simulation techniques are currently being developed which allow data entry through graphical techniques for general purpose simulations [14], for generalized environmental control and life support system design and analysis, [15] and for control system design [16, 17, 18]. Graphical interfaces greatly ease the data input process and reduce the problems associated with programming errors. The utilization of a graphical input simulation technique which accommodates the biophysical and physical processes involved in the CELSS system would be valuable in controlled system validation.

Iteration.

Finally, it should be noted that control synthesis is an iterative process of modeling, analysis, control algorithm development, simulation and testing, in which simplifying assumptions are gradually removed in the design process and, as hardware is developed, other assumptions made during theoretical development are altered.

APPLICATIONS TO THE CELSS SUBSYSTEM PLANT GROWTH UNIT

One of the subsystems in Fig. 1 is the Plant Growth Units and its associated components. Four configurations of the Plant Growth Unit subsystem are currently planned: the Crop Growth Research Chamber (CGRC), CROP, the Salad Machine, and EDEN. The CGRC is a ground-based unit in which precision control of environmental conditions will allow scientific research into plant growth in closed environments. CROP is a space-based unit with precision control comparable to the CGRC. The Salad Machine is a space-based unit designed to produce small amounts of salad vegetables for the crew. EDEN is a fully cycling space-based unit which will produce 10 to 15% of the food supply for the crew. The CGRC prototype instrument is currently under development.

It can be seen that each of these four configurations are specific physical realizations of the generic Plant Growth Unit subsystem. They differ from one another in performance specifications, degree of linkage to the remainder of the CELSS, and specific control component requirements to perform analogous functions in their particular design operating environments. Nevertheless, the functional analogy among them suggests a commonality of approach to modeling and control issues.

The CGRC Concept.

Fig. 2 is adapted from the CELSS reference configuration of Fig. 1. The interfaces of the storages which act as sinks and sources for the Plant Growth Units and associated control units with the remainder of the CELSS system have been removed. It is evident that this subsystem is functionally analogous to the CGRC. In the CGRC, the storages which had provided linkage to the remainder of the CELSS system have been made sufficiently large so that they can supply all the inputs (e.g. water, nutrients, carbon dioxide) and receive all the outputs (e.g. transpired water, oxygen) required for the plant growth subsystem. By providing sufficiently large storages, ideal closure conditions of a complete CELSS can be emulated by the CGRC.

The control issues for the CGRC are related to regulation of air temperature and humidity and atmospheric composition and pressure within the shoot zone and regulation of nutrient solution temperature, composition and pressure within the root zone of the plant growth chamber. The design range and tolerances of the shoot zone and root zone environmental conditions are given in Table 1. By controlling these conditions, the response of plants to conditions within the ideal subregion of the fundamental niche or to conditions in the remainder of the region of the fundamental niche can be examined. The latter may represent emulation of suboptimal closure conditions. Studies of crop responses to the extent of the range of environmental conditions will assist in establishing uncertainty bounds on the functional response of the plant growth unit. These bounds can be used in the representation of uncertainties for the Plant Growth Unit subsystem as a component in the study of control needs for the complete CELSS. A detailed description of the CGRC is given in [19].

The dynamic processes in both the shoot zone and the root zone of the plant growth chamber are profoundly coupled to those of the plant. Internal processes within the plant couple the shoot zone and root zone dynamics. A complete CGRC system analysis and control system synthesis must take into account the dynamics of the shoot and root zones and those within the plant. An initial simplifying assumption that the within plant coupling processes are weak allows separate preliminary analysis of the shoot zone and root zone dynamics. In later iterations of the design process, this assumption may be modified.

Description of a Proposed System.

Fig. 3 is a schematic model of the plant growth chamber and the components of a proposed system to regulate the shoot zone environment. The plants receive radiant energy from a light source above the chamber (not shown). Air flow into the chamber is assumed to be sufficient to assure that uniform conditions exist in the atmospheric control volume within the chamber and surrounding the plant canopy control volume. Gaseous exchange of carbon dioxide, water vapor and oxygen occurs between the canopy and the atmosphere. Air enters near the top of the upper chamber and is thoroughly mixed with the air in the upper portion of the chamber. The resulting mixture flows between the walls and the baffle formed by the plant support surface into the lower portion of the chamber and then into the duct work located near the bottom. A filter is provided to remove particulates from the air as it leaves the chamber. Air flow out of the filter is affected by the controllable orifice flow area of a valve. A portion of the air flow is diverted, by means of a controllable flapper valve and fan, into a gas separator which removes excess oxygen or carbon dioxide. A centrifugal pump (blower) serves to compensate for pressure losses within the system and provide the required air movement within the system. Makeup gases are injected into the flow stream to maintain the required atmospheric composition. A portion of the flow is diverted through a dehumidifying heat exchanger, where the condensate is removed from the system. Two variable flow area orifices are present one each in the flow path through the dehumidifier and in the parallel bypass. The orifice flow areas are variable in order to regulate the mass flow ratio of the paths. The air in the two flow paths is mixed and flows through a section of duct work. A portion of the flow is diverted through either a heater or a cooling heat exchanger. Three variable flow area orifices are present one each in the flow path through the cooling heat exchanger, the heater and the parallel bypass. The orifice flow areas are variable in order to regulate the mass flow ratio of the paths. Since meeting performance specification is considered paramount to economic constraints in this design concept, two heat independently controlled heat exchangers are utilized in humidity control and temperature regulation. The flows are mixed and flow through the duct work into the chamber inlet.

Control Focus for the CGRC.

The initial focus of control for the CGRC is in developing the strategy for variation of the available inputs (blower torque, valve apertures, etc.) in order to meet the chamber environmental tolerance requirements. The performance goals contain stringent tolerances on the acceptable region of the state space. The nature of the performance goals for the CGRC and the degree of closure of the system suggest that it is sufficiently different from other closed environmental chambers [20] that a control design based upon a mathematical model of the system is warranted. Some of the system components, particularly the biological, are inherently variable [21]. Their functional responses to environmental conditions are nonlinear and exhibit a considerable degree of uncertainty. These goals and characteristics suggest robustness as a control objective and a continuous time, state space mathematical modeling approach to the development of the control strategy.

Modeling Procedure.

The primary step in the modeling procedure involves the development of a symbolic model of the system. The symbolic model for the shoot zone of the CGRC represents the thermodynamics and fluid mechanics processes which are assumed to be significant in governing the dynamics of the system. Initially, attention has been focused on dynamics which occur, it is assumed, rapidly in comparison to plant growth. The following processes are accounted for in the symbolic model: mass and energy storage, fluid inertance, pipe friction, flow splitting and merging, duct expansions and contractions, flows through orifices and porous media, gas injection and removal, mechanical energy storage due to rotational inertia in the blower, isentropic compression in the blower, molecular diffusion between the chamber air and storages internal to the plant canopy, water transport within the plant, convective and radiative heat transfer, absorption of photosynthetically active radiation, and binding (release) of energy into (from) biochemical form.

In the following step, the symbols representing the constitutive relationships describing these processes are linked in a structure which illustrates the manner in which the processes interact. The mathematical expressions which describe the physical laws governing these constitutive relationships are combined with the equations which describe the structure of process interactions.

The details of a symbolic model which has been developed for the shoot zone of the CGRC are contained in [20]. The assumptions used in deriving the primary equations are developed in detail. Sample process equations and structural equations of the molar component and energy component of the symbolic model are also illustrated. The equations which are derived from the symbolic model relate the partial pressures of each atmospheric component, total pressures, mass or molar flow rates (hence velocities, transpiration rates, etc.), air temperatures, plant canopy temperature, etc. for the plant growth chamber and control system components. An illustration of some of the equations describing the thermodynamics and fluid dynamics of the shoot zone of the plant growth chamber of the CGRC which result from this approach appears in Appendix A.

<u>Future Work.</u>

The equations describing the dynamics of the total system, in state variable form, remain to be fully developed. These equations may be used to analyze system properties previously discussed, e.g. (1) location of equilibrium points, (2) stability at equilibrium points, (3) stability robustness at stable equilibrium points, (4) controllability, (5) observability, (6) system variable coupling, etc. The state variable form of the equations, including system uncertainties and disturbances, may then be used to seek robust control algorithms as required. The control system design can then be tested utilizing scenario studies on a simulation model. Should the system configuration as currently proposed fail to meet the required performance, a redesign can be made by reformulating the mathematical model. Additional processes, such as those affecting crop shoot-root interactions, may be added in order to model the behavior of the system in response to root zone environment disturbances and control inputs. Processes which affect longer term phenomena, such as biomass production, may be added in order to model system behavior over a growth cycle. As the development of the physical system progresses, the model can be modified as necessary to reflect the properties of the actual hardware as determined by system testing.

CONCLUDING REMARKS

Several issues in modeling and control have been discussed as they relate to problems in the analysis and synthesis of CELSS systems. These issues have been couched within a systems control framework in order to demonstrate how they might be addressed effectively utilizing the techniques of that discipline. A perspective has been presented of the Crop Growth Research Chamber (CGRC) as one version of the Plant Growth Units subsystem, one of the hierarchical levels of control to be addressed in the overall CELSS design. The initial steps to CGRC design which have been taken from a systems control theoretic pespective have been presented and an example of the equations which describe the thermal and fluid dynamics of the shoot zone of the plant growth chamber of the CGRC has been illustrated. Suggestions for future efforts to be pursued using that approach have been outlined.

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APPENDIX A

Example Dynamic Equations - Shoot Zone

- Energy

Chamber air

$$\dot{T}_c = (c_{v_{co_2}} M_{co_2} N_{co_2\ c} + c_{v_{o_2}} M_{o_2} N_{o_2\ c} + c_{v_{n_2}} M_{n_2} N_{n_2\ c}$$
$$+ c_{v_{h_2o}} M_{h_2o} N_{h_2o\ c})^{-1}$$
$$\{+ q_{conv_{lf}} + q_{conv_s} + \sum_j q_{conv_{sj}} + q_{conv_{cp}} + q_{arad_c}[H_2O,\ CO_2]$$
$$+ T_i\ (c_{p_{co_2}} M_{co_2} n_{co_2\ i} + c_{p_{o_2}} M_{o_2} n_{o_2\ i} + c_{p_{n_2}} M_{n_2} n_{n_2\ i}$$
$$+ c_{p_{h_2o}} M_{h_2o} n_{h_2o\ i})$$
$$- T_c\ (c_{p_{co_2}} M_{co_2} n_{co_2\ o} + c_{p_{o_2}} M_{o_2} n_{o_2\ o} + c_{p_{n_2}} M_{n_2} n_{n_2\ o}$$
$$+ c_{p_{h_2o}} M_{h_2o} n_{h_2o\ o})$$
$$- T_c\ (c_{p_{co_2}} M_{co_2} n_{co_2\ p,p})$$
$$+ T_{cp}\ (c_{p_{o_2}} M_{o_2} n_{o_2\ p,p} + c_{p_{h_2o}} M_{h_2o} n_{h_2o\ p,tr} + c_{p_{co_2}} M_{co_2} n_{co_2\ p,r})$$
$$+ \tfrac{1}{2}\ u_i^2\ (M_{co_2} n_{co_2\ i} + M_{o_2} n_{o_2\ i} + M_{n_2} n_{n_2\ i} + M_{h_2o} n_{h_2o\ i})$$
$$- \tfrac{1}{2}\ u_o^2\ (M_{co_2} n_{co_2\ o} + M_{o_2} n_{o_2\ o} + M_{n_2} n_{n_2\ o} + M_{h_2o} n_{h_2o\ o}) - P_c\ \dot{V}_c\}$$

Canopy

$$\dot{T}_{cp} = \{q_{arad_{cp}}[PAR] + q_{arad_{cp}} - q_{erad_{cp}} - q_{conv_{cp}} - q_{p,p}$$
$$+ q_{p,r} - q_{p,tr}\}/C_{T_{cp}}$$

Growing surface

$$\dot{T}_s = \{q_{arad_s} - q_{erad_s} - q_{conv_s} + q_{rz}\}/C_{T_s}$$

• Continuity

$$\dot{N}_{n_2\ c} = n_{n_2\ i} - n_{n_2\ o}$$

$$\dot{N}_{co_2\ c} = n_{co_2\ i} - n_{co_2\ o} + n_{co_2\ p,r} - n_{co_2\ p,p}$$

$$\dot{N}_{o_2\ c} = n_{o_2\ i} - n_{o_2\ o} - n_{o_2\ p,r} + n_{o_2\ p,p}$$

$$\dot{N}_{h_2o\ c} = n_{h_2o\ i} - n_{h_2o\ o} + n_{h_2o\ p,r} + n_{h_2o\ p,p} + n_{h_2o\ p,tr}$$

Example Functions - Shoot Zone

$$q_{\mathrm{arad}_{cp}} = \alpha\ A_{cp} \sum_j F_{cp,j}\ q_{\mathrm{erad}_j}$$

$$q_{\mathrm{erad}_{cp}} = \epsilon\ \sigma\ A_{cp}\ (T_{cp} + 273)^4$$

$$q_{\mathrm{conv}_{cp}} = h_{\mathrm{conv}_{cp}}\ A_{cp}\ (T_{cp} - T_c)$$

$$q_{p,r} = \lambda[T_{cp}]\ A_{cp}\ E$$

$$A_{cp}\ E = n_{h_2o\ p,tr}\ M_{h_2o} = A_{cp}\ \frac{\rho_a\ (\omega_{cp} - \omega_c)}{r_l^{h_2o} + r_b^{h_2o}}$$

$$r_b^{h_2o} = r_b^{h_2o}\ [W_l,\ D_l,\ u_c]$$

$$r_l^{h_2o} = r_l^{h_2o}\ [T_{cp},\ C_{co_2\ cp},\ RH_c,\ \Psi_{cp}]$$

Definitions

T	temperature - °C
N	moles
n	molar flow rate - mol/sec
M	molecular weight
u	velocity of the air mass - m/sec
q	heat/energy transfer rate - watts
c_p	specific heat (constant pressure) - watt sec/gm K
c_v	specific heat (constant volume) - watt sec/gm K
C_T	heat capacitance - watt sec/K
P	static pressure - Pa
V	volume - m^3
PAR	photosynthetically active radiation
R	ideal gas constant
ϵ	emissivity
α	absorptivity
σ	Stephan-Boltzmann constant
A	area - m^2
$F_{i,j}$	radiation shape factor between surfaces i and j
h	heat transfer coefficient - watts/m^2 K
λ	latent heat of vaporization - watt sec/gm
E	transpiration rate per unit area - gm/m^2 sec
RH	relative humidity
r	diffusion resistance - sec/m
C	concentration - grams/m^3
Ψ	water potential - Pa
W	effective dimension across direction of air flow - m
D	effective dimension in direction of air flow - m
ω	humidity ratio
ρ	density - gm m^{-3}
$\cdot$	derivative with respect to time - sec^{-1}

Subscripts

c	chamber atmosphere
cp	plant canopy
s	growing surface
sj	surface j
lf	light filter surface
co_2	carbon dioxide
o_2	oxygen
n_2	nitrogen
h_2o	water vapor
i	incoming air mass
o	outgoing air mass
p,r	dark respiration of the plant canopy
p,p	photosynthesis of the plant canopy
p,tr	transpiration of the plant canopy
erad	emitted radiative
arad	absorbed radiative
conv	convective
rz	root zone
l	effective leaf
b	boundary layer
a	dry air

TABLE 1. Design range and tolerances set for the Crop Growth Research Chamber shoot zone and root zone environmental variables.

<u>Shoot Zone</u>	
Air temperature	5-40° C ±1° C
Relative humidity	35-90% ±2% of set point
Carbon dioxide concentration	25-5000 ppm ±0.2% of set point
Oxygen concentration	5-25% ±5% of set point
Nitrogen concentration	75-95% ±5% of set point
Gage pressure	0.5" H_2O ±0.25"
Air velocity	0.5 m sec^{-1} ± *
Photosynthetic photon flux	0-3000 μmoles m^{-2} s^{-1} ± 10 μmoles m^{-2} s^{-1}
Surface temperatures	Air temperature + 2° C
<u>Root Zone</u>	
Solution temperature	5-40° C ±1° C air temperature + 2° C
pH	4.0 - 8.0 ±0.2
DO	> 80% saturation
Nutrient concentration	0 - 500 mmol ± *

* tolerance not determined

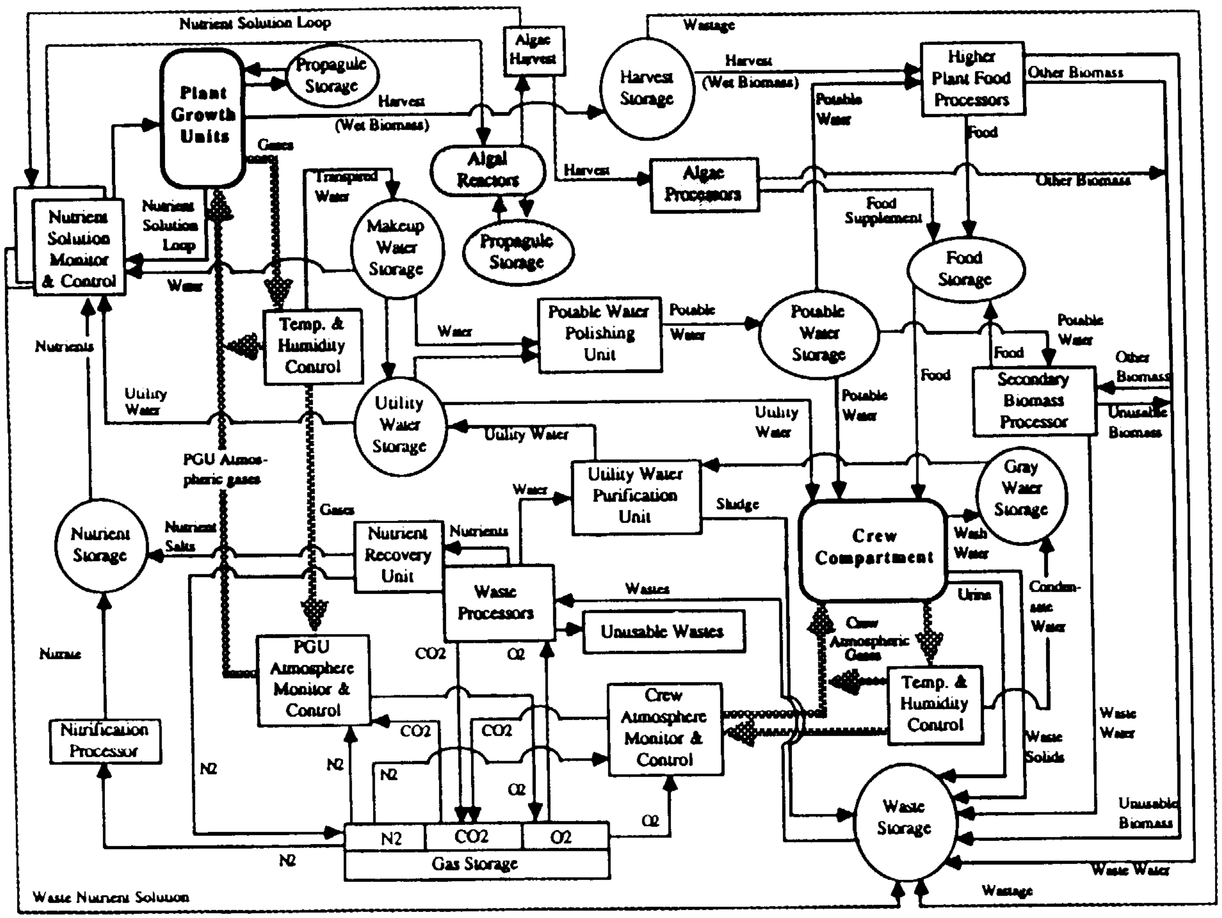

Fig.1. CELSS initial reference configuration. (From [1].)

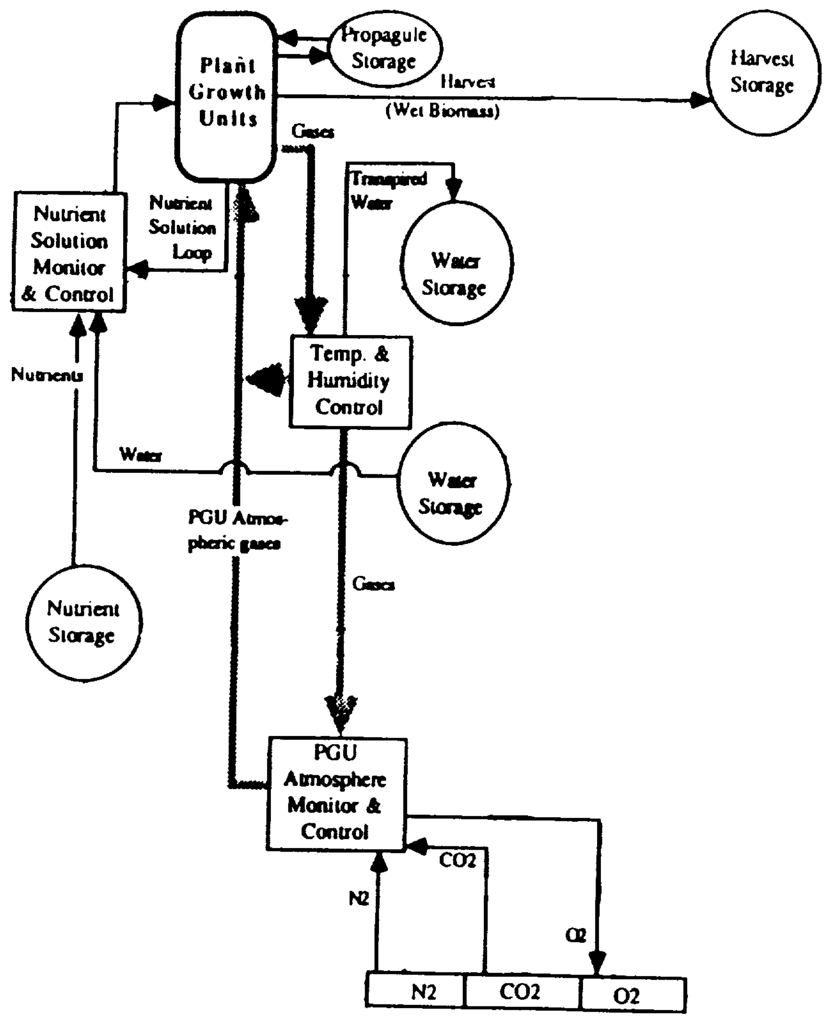

Fig.2. Crop Growth Research Chamber functional analogy to the CELSS Plant Growth Units subsystem.

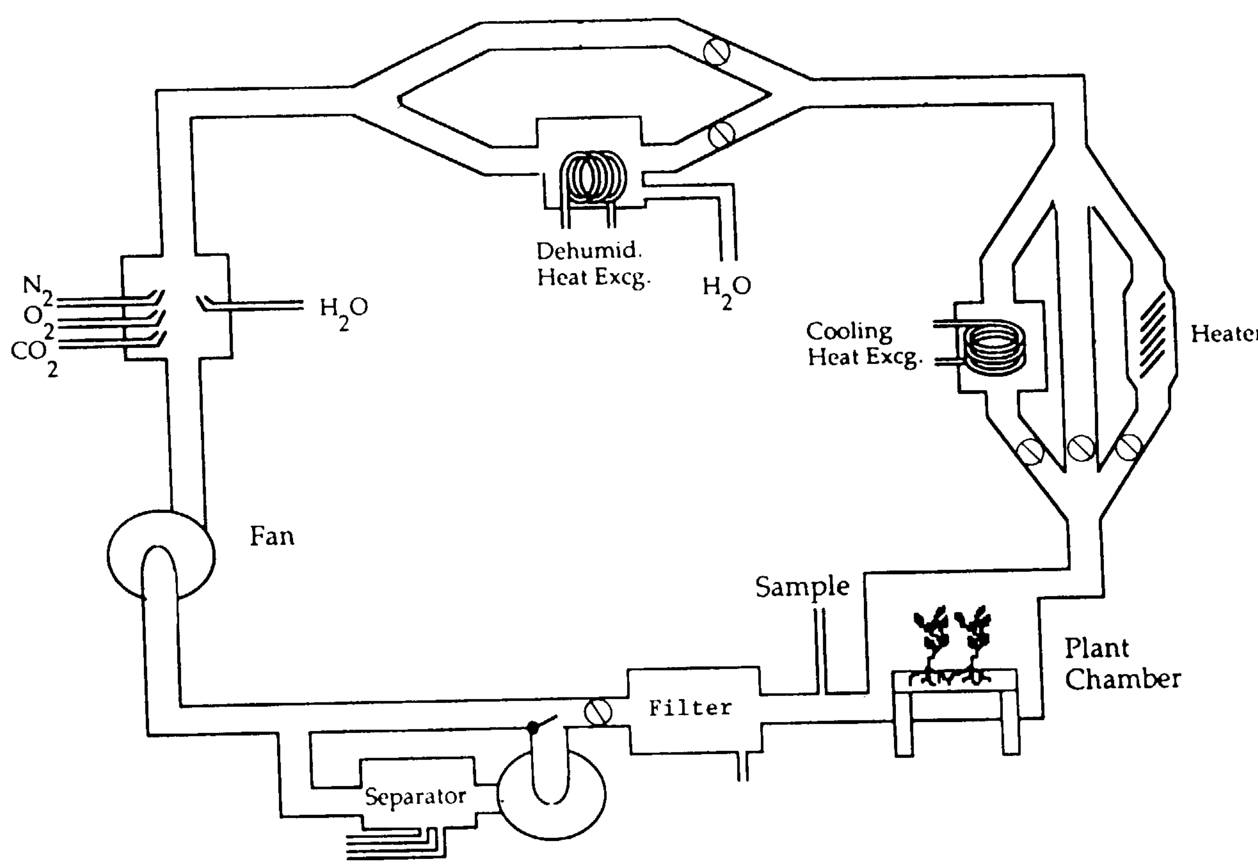

Fig.3. Schematic model of the Crop Growth Research Chamber.