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Paper Session I-A - Hands-off Farming in Space

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Hands-off Farming in Space
(Development of an Autonomous Biomass Production System for Supporting Human Exploration in Space)

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Abstract
This paper focuses on the mechanization of a biomass production system (BPS) in enclosed environments for space agriculture. It requires an intelligent computer for the autonomous adjustment of controlled elements and a robotic system for measurement of plant growth and harvest. This research is to develop and integrate a BPS framework that enables autonomy, monitoring, diagnosis, fault detection and correction, and production optimization. The key feature is an integrated health monitoring and production management and control system (IHPMCS) implemented with the robotic system. IHPMCS is an integrated algorithm integrated into an embedded computer that can process biomass production data in real-time based on measurements of production elements in the chamber. The concept proposed is to take the human expert out of the control loop and build his expertise into the computer to yield an autonomous BPS. This will provide an optimal and autonomous biomass production capability so that BPS can maximize the ability to grow plants and allow astronauts to be more involved in scientific or technical activities. This is a collaborative research between academia (University of Central Florida), industry (Dynamac), and government agency (NASA) at Kennedy Space Center.

1. Introduction

Reliable technology for biomass production in space to provide food has not yet been developed. This system, in order to be effective, will need an intelligent computer for the adjustment of controlled elements and robotics for the collection of plant growth measurements in the biomass production volume. These mechanism will replace human labor on space missions or applications for other planets; an autonomous controlled environment using Biomass Production System will be required to successfully grow plants autonomously in support of manned space missions

It is feasible to develop a bio-production model since plants generally grow in a predictable way under specific conditions. Such a model that characterizes an optimal growth pattern for a tomato crop will be developed and used as a truth-reference model. Recorded differences between the desired growth parameters and the actual measured parameters more than a given threshold value, would cause the detection of an abnormality in one or more growth parameters. If this were to occur, the computer would switch to a diagnostic mode and search a predetermined intelligent data file for the necessary control correction to remedy the problem. The unique feature of this approach is the use of a robotic system instead of human labor to gather sensor data (including visual inspection images) within the biomass production volume and, in real-time, have the intelligent computer to analyze the measurements and send the proper control corrections to the relevant actuators to correct the abnormality in near real-time, hence, health monitoring and intelligent control.

2. Intelligent systems for the autonomous adjustment of controlled elements

The concept of using plants to provide a bioregenerative life support system (BLSS) has been studied since the 1950's. The early work focused on using algal systems for O_2 production and CO_2 removal from closed systems, Meyers (1954), Eley and Meyers (1964). Russian researchers pioneered the use of higher plants in large-scale closed environmental tests during the 1960's and 1970's Gitelson and Oklandikov (1994). The environmental and design considerations necessary for both microgravity and gravity-based BLSS were the subject of a recent review by Wheeler et al (2001).

Because of the harsh environment in space, growing crops for life support will require a protected environment. Light, CO_2, temperature, humidity, mineral nutrition, pressure and radiation protection will all require careful management in order to optimize BLSS performance. Drysdale et al. (1993, 1994) defined the various failure modes that could be implemented, and Fortson and Stutte (1996) made a general assessment of different failures. These included loss of CO_2 control, poor temperature and relative humidity control, and changes in light intensity. Changes to each of these parameters directly impact the O_2 production, CO_2 removal, water purification, or food production in the BLSS.

There is extensive literature describing interactions between environmental factors that must be considered in developing a BLSS, Stutte et al (1996, 1999), Wheeler et al. (2001), and references therein. The PESTO experiment, which grew wheat onboard the International Space Station during Increment IV, was able to document the direct effects of temperature and relative humidity changes on photosynthesis and transpiration under both 1g, Stutte et al (2001, 2002) and microgravity conditions. The plant component of a BLSS will not be functioning in isolation, but be incorporated into an overall environmental control system. Because of the dependence of the life support functions on environmental control, it is critical that the operational limits of the BLSS are defined and models developed are tested to insure that optimal growth conditions are maintained. The integration of validated crop models with automated monitoring and control systems is essential to implementation and utilization of BLSS on long-duration space missions

3. Robotic system for the measurements of plant growth and the harvests

Local and Global measurements

There are two levels of measurement spatial resolution required, which depends somewhat on the size of the growth chamber. First, for precise growth modeling and plant status monitoring, local measurements need to be taken at the individual plant level. In large systems, this can become very impractical from both a cost and sensing complexity standpoint. An autonomous Inspector robot could roam the growth chamber/greenhouse and collect local data samples at an individual plant level to give accurate readings regarding the status of randomly selected plants, which would be representative of the chamber as a whole. However, real-time control of environmental conditions cannot be dependant on measurements, which vary spatially with time, unless measurements are geo-referenced and the elapsed time between repeated measurements at the same spatial location is less than the required control update frequency. This could become a problem in larger systems with one roving Inspector. Consequentially, it is appropriate and necessary to have a network of spatially fixed sensors, which can provide both an overall chamber and a quadrant-by-quadrant measurement of the critical environmental control inputs.

Parameter Sampling Consideration

Sampling is done to measure environmental parameters such as; CO_2 concentration, temperature, humidity, light, air velocity, etc., that affect the plant growth. With the requirement of compact size, a commercially available probe, which senses both temperature and humidity, is desirable. Sensors such as Silicon based Non-Dispersive Infra-Red (NDIR) Sensors, can be used to measure the amount of CO_2 in the biomass production system. These are used to determine of the rate of photosynthesis by the plant through the amount of CO_2 consumed. Light sensors need to measure the global and local light intensity from the light emitting diode (Red light at 670 nm and blue light at 470 nm can be used to support photosynthesis and proper plant development). A very compact commercially available photoelectric sensor needs to be located on end-effector for local light measurement compared to global light measuring sensor. Air Velocity Sensors such as bi-directional anemometer probes can be used determine the airflow as well as the air intensity. Photosynthetic Photon Flux (PPF) sensors can measure the intensity of radiation between 400 and 700 nm, which are the most important wavelengths for photosynthesis and plant growth. Photosynthetic Photon Flux Quantum sensor or similar sensors are recommended to measure the PPF.

Plant sampling

Plant stresses can affect the plant growth considerably. Periodic plant material sampling needs to be performed to monitor overall plant health. Early detection of vegetation stress by passive remote sensing depends largely on identifying the spectral regions in which vegetation reflectance is most responsive to unfavorable growth conditions. For individual leaves, increased reflectance at visible wavelengths (400-700 nm) is generally the most consistent response to stress within the 400-2500 nm range. Plant Fluorescence Sensors can be implemented on the end-effector to detect plant stress. A Chlorophyll sensor will be mounted on the end-effector to take plant sampling from different regions of the plant canopy. Periodic chlorophyll sampling will be useful in determining possible plant diseases or deficiencies and in monitoring overall plant health. Sensors similar to Fluormetry Chlorophyll Sensors can be used for this application.

A Video Monitoring system can be used to guide the robotic system. The camera system implemented on the end-effector should be very compact. Considering the requirements of compact size, resolution higher than 300 pixels, ease of interface and transmission to a monitor and power supply with a low voltage and low consumption, commercially available color cameras similar to surveillance and video security cameras can be utilized.

4 Robotic Harvesting System

4.1 Robotic System in use
Control requirements
Processes and components in the system must be controlled continuously. Plant growth and health must be monitored in the presence of dynamic variations. Typically, control and monitoring are done conventionally using standard off the shelf control/sensor modules. Advanced controls (such as nonlinear robust control, adaptive control, etc.) are ideal candidates in the design of an autonomous system operating in an unknown and changing environment. However, space-bound computers have very limited computational power in analyzing all data real-time and synthesizing all control signals.

Dexterous End effector (ALSARM) for sampling and harvesting
FSI and KSC have been co developing a dexterous End Effector, ALSARM. The ALSARM is composed of a three degree-of-freedom robot manipulator that has automated control. The ALSARM is to be equipped with an End Effector that is capable of retrieving samples from the BPC. End-Effector (EE) System is required to grip, cut, and move plant material. To achieve these goals, the EE will utilize four motors to control the pitch, yaw, and roll motion along with gripping. The cutting of the vegetation sample is achieved through the use of passive means.
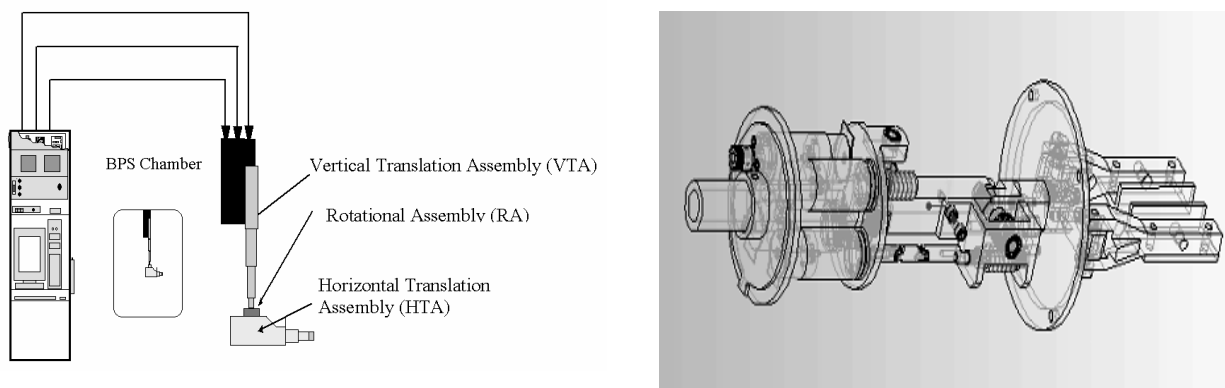

Figure 1: ALSARM design and End Effector Schematic

One of the requirements of the End-Effector is to harvest different types of frui`t. This has led FSI to adopt the changeable End-Effector. A cone and adapter method is proposed for easy change of the End-Effector. The cone of each end-effector will be compatible with a single adapter in the manipulator.

Key features of End Effector
FSI is currently in the process of engineering to upgrade the performance of End Effector. The upgraded End Effector will have the following additional functions:
- Exchangeable tool functions: Depending on the plant type, the End Effector is required to be adaptively designed to harvest it. The adaptive tool will increase the productivity as well as secure sampling or harvesting.
- Local measurement sensors: The End Effector will be designed to accommodate more sensors. This will require improvement to its structural design, and its precision and reliable functions.
- Robustness control with optimal design: The weights of plants are varying depending on the size and type. To accommodate this uncertain condition, the End Effector control is required to be robust, bound by weight limits. However, the power for the actuators should be optimally designed to save energy.

Manipulator

The robot manipulator has two telescoping arms with a vertical, a horizontal, and a rotational joint. The ALSARM End Effector is an extension of the robot manipulator's horizontal-telescoping arm. The End-Effector is mounted at the end of the telemag. The End-Effector that goes on the telemag of the ALSARM is capable of retrieving samples from the BPC. The optimum design of manipulator is also an important factor for productivity. The current system is designed for the cylindrical coordinate system. However, the manipulator platform can be modified and optimized depending on working area. FSI is actively researching robotic harvesting system with mobile platform. Kinematics and Dynamics of robotics on mobile platform is very complicated and its control algorithm is important to optimize its performance.

4.2 Key features for the system

In summary, the proposed control and design concept is unique in that the control system is not relying on human input and it has intelligent functions to ensure the goals. The following are the key features of the system:

- An integrated health monitoring production management and control system (IHPMCS) implemented with the robotic system
- Integrated algorithms embedded into a computer that can process biomass production in real-time based on measurements of production elements in the chamber.

By successful implementation of the above key features, we are expecting to have the following results:

- To take the human element of the control loop
- To build his expertise into the computer to yield an autonomous BPS
- To provide an optimal and autonomous biomass production capability
- To maximize the ability to grow plants in BPS
- To allow astronauts to be more involved in scientific or technical activities

5. Development and integration of BPS framework

Autonomy, monitoring, diagnosis, fault detect and correction

Current controlled ecological life support systems cannot measure the dynamic behavior of the system in real-time. We will measure abnormal dynamic parameters to monitor an out-of-tolerance condition of the system. These parameters can be predictors of impending failures in those systems. As shown n Figure 2, the proposed feature adds a new dimension to existing control mechanism that will greatly enhance the visibility of the "System State" which, in turn, increases the reliability of the test and evaluation process, and autonomous operations over those currently in use. This processing technique also promises the real-time detection of abnormal data flow conditions and the automatic identification of the specific area (component/subsystem) causing the fault condition. This attribute speeds up diagnostic analysis to near real-time and provides enough time to stabilize the system by parameter correction. The measurement and actuator elements must now be analyzed to understand how the increased "reliability" and "parameter correction" requirements can be implemented into the systems to support autonomous operations. The proposed system will open a window to achieve optimization of planned (deterministic) production that is essential for human exploration in the solar system.
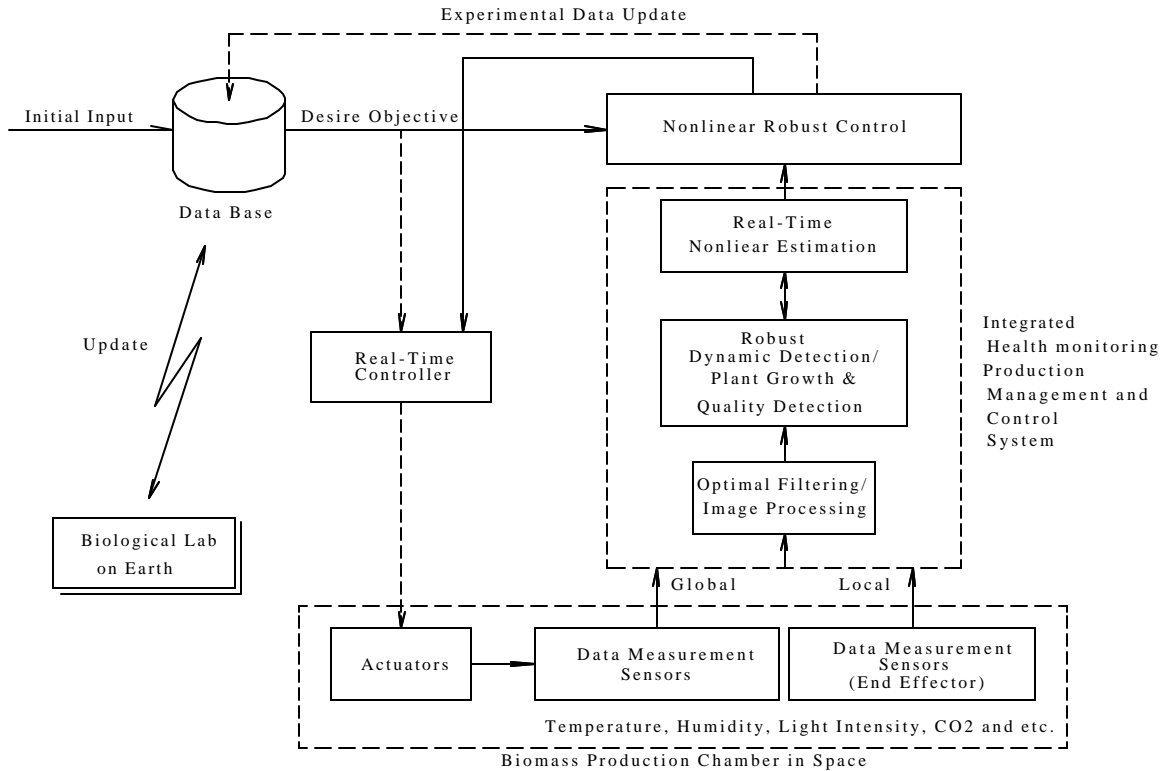
Figure 2 Control System Block Diagram

Production database and optimization

The optimized control of environmental parameters will result iddn high productivity. Since these requirements differ for each plant, monitor and control of them are important. For example, potato and soybean suggest that maximum yields might be achieved near 800 to 1000? mol m^{-2} sec^{-1}, however, some plants, higher PAR (Photo synthetically Active Radiation) levels may be undesirable because of injuries such as tipburn (e.g. lettuce) and leaf chlorosis, particularly under high-intensity discharge lamps. In the case of this investigation the tomato crop will be emphasized. Temperature is another important control issue. Many of the crops considered for life supports prefer warmer temperatures ranging from 25°C to 30°C, where as potatoes and wheat do well at cooler temperatures ranging from 15°C to 20°C. In addition to these parameters, pressure, CO_2 gas rate, and relative humidity should be closely controlled for increased productivity. With biologists' collaboration, an optimized database for plant growth environment conditions will be created. This preliminary database will be initially utilized as a model for the reference of monitoring environment. Integrated Health Monitoring and Production Management and Control System (IHPMCS) is a development of an integrated control framework that enables autonomy, monitoring, diagnosis, and fault-recovery and self-healing execution at execution at both levels of dynamic and steady state control. In order to overcome the major obstacles, an intelligent control framework will achieve the following technical objectives: By overcoming two major obstacles, the proposed intelligent control framework can achieve the following technical objectives.

- Robustness in a changing, uncertain environment: The system is capable of identifying external disturbances and operating conditions using the standard sensors and computation power on board, which can be done using advanced nonlinear robust control algorithms. The control system must also be robust so that all uncertainties within actuator capability can be compensated for.
- Fault tolerance: Upon automatic detection of a failure of any component, the control system can maintain system functionality by switching to the redundant backup. More importantly, in the case

that no more redundant part is available; the control system is capable of automatically adapting and achieving the best possible performance.

- Autonomous and self reconfiguration: Robust identification and control are integrated so that the system is capable of self-activating through environment diagnosis, self calibrating, self deploying, and self adjusting by intelligent reasoning. Upon detecting a fault, the robust estimation module will provide sufficient information for transient control after excluding feedback from faulty sensors.
- Intelligence: Model-based reasoning capability will be an integrated part of monitoring, diagnosis, and recovery.

Evaluation of plant growth

Machine vision and other spatial imaging techniques will provide the corner stone for the IHPMCS robotic inspection. A visual surveying technique will be used to locate the surface and control the end-effector's approach towards the plant canopy. Once the Inspector has locked in on the plant canopy and achieved the appropriate length to surface, the Inspector will scan the plant canopy evaluating plant health indicators in real time using the full sensor suite. When necessary, the Inspector can zoom in on the canopy for taking surface measurements. In order to fully implement the envisioned inspection capabilities, significant research will need to be conducted to develop a library of plant status indicators. These indicators will need to be identified through a systematic and controlled study of the target plants responses to known diseases, nutrient and environmental deficiencies. It does however, point toward the need for a significant ongoing research effort to categorize plant health status indicators. With this library on-board, the Inspector can roam a space based IHPMCS and detect plant abnormalities so that the IHPMCS can make control decisions to maintain crop productivity.

6. Conclusions

The prototype robotic system has been successfully operated in a Biomass Production Chamber at KSC. The ALSARM end effector is currently in manufacturing and will be interfaced with the robot manipulator, which will enable us to measure environmental variables as well as to harvest plants in the chamber. Artificial disturbance or environment data such as temperature or light intensity will be filtered through the computer system, and the control system will optimally order the actuators such as heater or LED light source after comparing initial desired values. Remote system control to improve desired values from earth will be another testing item in the future. The biologist can continue to update plants' growing conditions on the earth and implement the information via communication systems. The upgraded manipulator with more features will be implemented after completing feasibility studies, and development of new algorithm to incorporate hardware will remain as future tasks.

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