Patil_2002

DESIGN OF AN AUTONOMOUS HARVEST ROBOTIC SYSTEM AND A BIOMASS CHAMBER ON MARS

C. Ham, R. Johnson, L. Retamozo, R. Patil, H. Choi and J. Brandenburg
Florida Space Institute / Department of Mechanical, Materials and Aerospace Engineering
College of Engineering and Computer Science
University of Central Florida
Orlando, FL 32816, USA

ABSTRACT

In situ food production will become essential in the expansion of human exploration in the Red Planet. When colonizing Mars, consumables re-supply from the earth will become not only very costly due to constraints on mass and volume, but also may cause potential psychological problems to astronauts having a diet mostly of packaged foods. The diverse technologies required for the biomass production on Mars, providing food and advanced life support operations have not yet been adequately integrated and demonstrated. In this paper, we develop an autonomous harvest robotic system and a biomass chamber on Mars to supply fresh vegetables and fruits as a dietary supplement for the crew. The unique feature of our approach is the use of robotic systems to replace human labor and provide optimal environmental conditions for plant growth. The system will provide an optimal and autonomous biomass production capability to maximize the ability to grow plants with minimal human input. First, this paper presents development of a biomass chamber and selection of vegetables and fruits that can be suitably grown in controlled environments. Then, an advanced robotic system is proposed in order to maintain the biomass chamber autonomously. It harvests, transports, and stores the fruits via remote operator commands. Sensors mounted to the robotic system will monitor the biomass chamber environments such as temperature, humidity, light intensity, etc. An integrated control system is also presented that provides stable operation of the robotic system assuming optimal growth and health of the plants under production. It provides autonomy, monitoring, diagnosis, fault-recovery and self-learning execution. Finally, we introduce our prototype system that has been operated on a near-continuous basis in the Controlled Ecological Life Support System facility at Kennedy Space Center.

KEY WORDS: Biomass Production Chamber (BPC), Robotic Manipulator, End-effector, Autonomous Harvesting System, Model Based Self-Configuration.

1. INTRODUCTION

Ways to reduce the risk and cost of traveling to Mars have been well examined throughout the last two decades. One cost-reduction method is to reduce the mass requirements and to provide the food and life support systems through bio-regenerative power utilizing a BPC. The BPC is an essential structure. It would aid space-faring crews

in the generation of oxygen and food. The BPC also provides critical first steps in any terra-forming venture. For any such efforts, crew self-sustainability is critical.
Reliable technology for biomass production in space that will provide food has not yet been developed. This system, in order to be effective, will need to use robotics to augment mechanization or replace human labor. The proposed research will evaluate current technologies and identify critical improvements necessary for the creation of an Autonomous Biomass Production System (ABPS) that uses robotic systems. In space or on other planets a controlled environment using ABPS is required to successfully cultivate food plants. Without an autonomous system, crops may not be uniform and could not be grown in non-human rated environments, and may preclude human interaction. The ABPS can solve many problems associated with variability and accessibility of plant growth chambers more over such system can reduce the psychological burden of astronauts for harvesting and management. Such a system can maximize effective time utilization of astronaut. Consequently there is a timely need to build and test ABPS in order to develop algorithms that will maximize the ability to grow plants autonomously. FSI and UCF have actively participated in the BPC research activities at NASA performed at KSC on a regenerative life support system using hydroponics plant growth in a closed environment.

2. MARS ENVIRONMENTAL CONSTRAINTS

Requirements for the landing of initial NASA missions to mars include a position of ± 15 degrees of the Martian equator. Factors to consider in this region include temperature, pressure, solar irradiance and dust storms. Nevertheless, assumptions for the BPC will require slightly higher temperatures at the lower altitudes and seasonal variation will be insignificant. Consequently, expected daily temperature range selected for design purposes is 150K to 300K. However, depending on surface elevation, the pressure can range from 2 to 10 mbar. For the purposes of the BPC, atmospheric pressure will be assumed to be a near vacuum. Daily winds have been recorded to be only 0.5-0.9 m/s during the day and 4.5 m/s at night. However, both localized and global (originating in the Martian Southern Hemisphere) dust storms can reach up to 25 m/s. In the aphelion solar irradiance will be 473 W/m^2 while at the perihelion will be 718 W/m^2. Thus, BPC will be designed to withstand the worst-case environmental scenario. [1]

2.1 Physical limitation concepts

2.1.1 External Structure Requirements

The external structure must be deployed from a manned or unmanned vehicle and must have an internal frame structure that can be stowed in a tight payload compartment from which it can be deployed automatically. Due to the mass and power savings, transparent materials are considered as a good option, but should allow maximum light (400 – 700 nm) transmittance and be able to withstand ambient (Martian) UV radiation and other environmental parameters. Structural geometry should consider factors such as lighting harvesting efficiency, orientation with regard to solar movement across the sky, and capability to withstand pressure differentials (from inside to outside the BPC could range from 10 to ~50 kPa). [2]

2.1.2 Plant Growth Area Structure Requirements

Plant growth will be implemented providing adequate volume to accommodate crop growth and any projected materials handling, and be capable of withstanding the rigors of the Martian surface environment. Structural components should have minimal mass and be able to be stowed and deployed effectively.

2.1.3 Water and Nutrient System Delivery System Requirements

A solid media or fluid system will be implemented for providing water and nutrients to the plant root zone, management of mineral nutrients and root zone aeration should be considered. Similarly, a system that manages the mineral nutrients recollection and root zone aeration should be considered.

2.1.4 Lighting System Requirements

In general, plants need a light range transmittance between 400 – 700 nm, in order to sustain life. The incident light at the surface of Mars is a half of the incident light on Earth. Hence, a number of lighting schemes may be considered, that include artificial lighting systems. For the BPC plants to perform their functions properly, a mid-day intensity of 125 W/m^2 (400 – 700 nm), or about 500 mmol/(m^2 s) photosynthetic photon flux (PPF) is sought, with minimal intensities of at least 50 W / m^2 (~200 mmol / (m^2 s)) maintained at least for a 12 hour cycle each Martian day (minimum of ~2 MJ / (m^2 d) or 8 mol / (m^2 d)).[3]

2.1.5 Atmospheric Composition / Conditioning Requirements

Ventilation, temperature control, gas composition, relative humidity is important parameters in providing the appropriate environment for plant growth. The design concept must address the controls for providing a satisfactory environment. Atmospheric management will require separation and storage of photo synthetically generated oxygen (O_2), and systems or concepts for restoring carbon dioxide (CO_2) consumed by the plants.

2.1.6 Materials Handling Requirements

Depending on the management concept proposed, automation of plant harvesting and replanting might be required. Harvesting of crops would require removing plant materials for possible dehydration and storage. Edible materials might be separated and stored for crew arrival, or systems might be designed for human tending to reduce the need for automation. Similarly, replanting could be automated or operated as a human-assisted operation.

2.2 Temperature Control

For a Mars habitat, the cooling and heating requirements are major factors. During extremely cold night temperatures the BPC may require supplemental insulation schemes, depending on structural characteristics (e.g., nighttime covers). There may be a need to dissipate heat from the lighting system, while heat input may be required during the dark cycles. Thus systems that can collect, store, and distribute waste heat should be included in the design concept.

2.2.1 Environment Temperature Range Discussion

According to the 1996 Pathfinder mission data, temperature near a 40° North latitude during a Martian day ranges from 200K-259K. Nevertheless, assumptions for the BPC will account slightly higher temperatures at the lower altitudes. Seasonal variation will be insignificant. Consequently, expected daily temperature range selected for design purposes is 150K to 300K. [3]

2.2.2 Temperature Control Devices utilized

Polyurethane foam walls will serve as heat exchangers. Air circulation requires two 125W and two 150W blowers. The blower capacity is based on $246m^2$ of plant shelving. The air handling system provides from 3 to 4 air exchanges per minute, with air velocities ranging from 0.1 to 1.0 m/s. Heat rejection and humidity control will be accomplished by chilled water coils located at the outlets of blowers. The condensation that occurs on the coils will help to monitor the evaporation rates. Atomized streams of water implemented directly in the air stream provide supplemental humidification if needed.

Subsystem	Range of Operation
Air Revitalization System Oxygen Carbon Dioxide	18.5-23.45 % 300-5000μL/L
Chamber Pressure	101Kpa
Ventilation and thermal control Air temperature Relative Humidity Air Velocity	 15-35 °C 70-85 % 0.1-1.0 m/s
Leak Detection and Control Leakage Rate	1% of the chamber volume/day

Table 1 Atmosphere Supply and Control Requirements

2.3 Requirement of bio production (Crop Selection)

The temperature range and the other physical conditions of Mars play a vital role in Plant selection. A sample list of twenty-five acceptable plants has been collected which favor temperature range between 288.15 and 293.15 Kelvin. These plants have been selected

Beans	Soybean	Carrots	Grasses	Italian Calbrese
Dwarf Rice	Tomato	Algae	De Cicco Green Broccoli	Spinach
Lettuce	Arabidosis Thaliana	Snowball Cauliflower	Asparagus	Potato
Amaranthus	Cabbage	Beets	Wheat	Ivy
Strawberries	Onion	Oats	Barley	

Table 2 Biomass Production Candidates

for final review due to the fact that they are hardy species with high resistance to frost.

Among these candidates, sixteen will be brought to Mars in the bedding material as seeds. The growth of these plants will occur after the deployment of the BPC vehicle. Oxygen is needs inside the BPC are at 10-14% of total air volume. The plants were chosen on the following basis:

1) The Plants are high yielding and fast growing
2) The nutritious biomass of carbohydrates and proteins are relatively high
3) The ratio of edible to inedible portion of the plant is large
4) The food processing requirements are minimum
5) The likelihood of astronaut psychological and aesthetical acceptance is greater than for other selected plants
6) They are not tall, so multiple levels can be grown
7) Horticultural requirements are easily met through robotics
8) Their environmental requirements are easily met with minimum power usage
9) A large amount of information is available about each plant including genotypes

The plants finally selected after detailed study were: Wheat, Dwarf rice, Soybean, Potato, dry bean, Strawberry, Lettuce, Tomato, Onion, Broccoli, Spinach, Beets, Baby carrots, Amaranthus and Arabidopsis Thaliana.

3. ROBOTIC HARVESTING SYSTEM

3.1 Control requirement

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-shelve control/sensor modules. The problems arising in monitoring dynamic states needs to be resolved.

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.

3.2 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. [5][6]

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

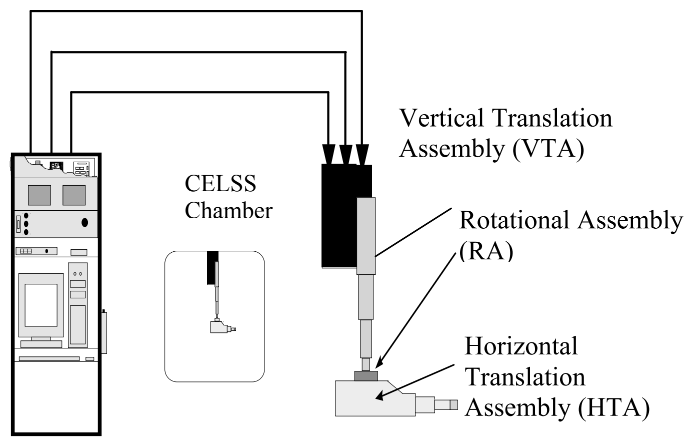

Figure 1: ALSARM design and control

3.3 Manipulator

The robot manipulator has two telescoping arms, a vertical a horizontal, and one rotational joint. The ALSARM End Effector is an extension of the robot manipulator's horizontal-telescoping arm. The End-Effector is supposed to be 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.

3.4 Biomass production chamber monitoring system

This mechanism is to operate in a Biomass Production Chamber (BPC). The BPC is an enclosed environment used for plant growth and oxygen regeneration. It is composed of two plant chambers. The BPC is to be sealed so that water vapor and air do not escape and the water can be recycled. The scientists in this program want to eliminate personnel entry, reduce the leak rate of air and water vapor, and obtain very consistent measurements inside the chamber. Sensors mounted to the End Effector will be capable of measuring temperature, infrared temperature, relative humidity, air speed, and light intensity. A computer is already programmed to take these measurements at hundreds of different points in the BPC. Another addition to the ALSARM is the placement of a viewing apparatus for manual direction. There have been for different designs for the End Effector. [8][9]

3.5 Control System for autonomous harvesting system

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. And, 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/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.

In summary, the proposed intelligent control system will reduce the cost, enhance reliability, and increase safety, so that BPC can be operated in an environment that could change significantly. The block diagram of the control system considered in this research project is shown in figure 2. The system basically consists of a set of actuators that drive the robotic system of the BPC. The system variables (or the states) are monitored by sensors. The measured signals will pass through optimal filters (such as a typical Kalman filter). The proposed real-time management configuration combines state-of-the-art tools available. Specifically, optimal filtering, nonlinear and robust estimation, nonlinear fault detection, nonlinear learning control, and the expert module are integrated in such a way that they complement each other. Analysis and design will be done using the nonlinear system theory, Lyapunov direct method, estimation and learning, and artificial intelligence techniques based on heuristic knowledge.

3.6 Unique features

The proposed intelligent control framework has a hierarchical structure and consists of the following layers/components:

1) Local control at the process/component level (bottom and local level).
2) Discrete monitoring and fault-recovery control (intermediate and local level).
3) Individual estimation and monitoring device (intermediate and local level).
4) Nonlinear learning control (intermediate and regional level).
5) Model-based reasoning for intelligent control (top and global level).

The Biomass Production Chamber (BPC) at NASA's Kennedy Space Center has been operated on a near- continuous basis for 6 years providing baseline data for using plants in closed, life-support systems in space. Total Biomass yields of the different crops (wheat, soybean, lettuce, and potato) were strongly dependent on total lighting provided to the plants and generally close to anticipated values based on university research and preliminary growth chamber trials; however, edible yields and harvest index have sometimes fallen short of anticipated values.

Based on this analysis of closed system plant growth it is shown that a well-developed ABPS robotic system can effectively reduce crew time and increase yields by having a consistent process to improve crop production.

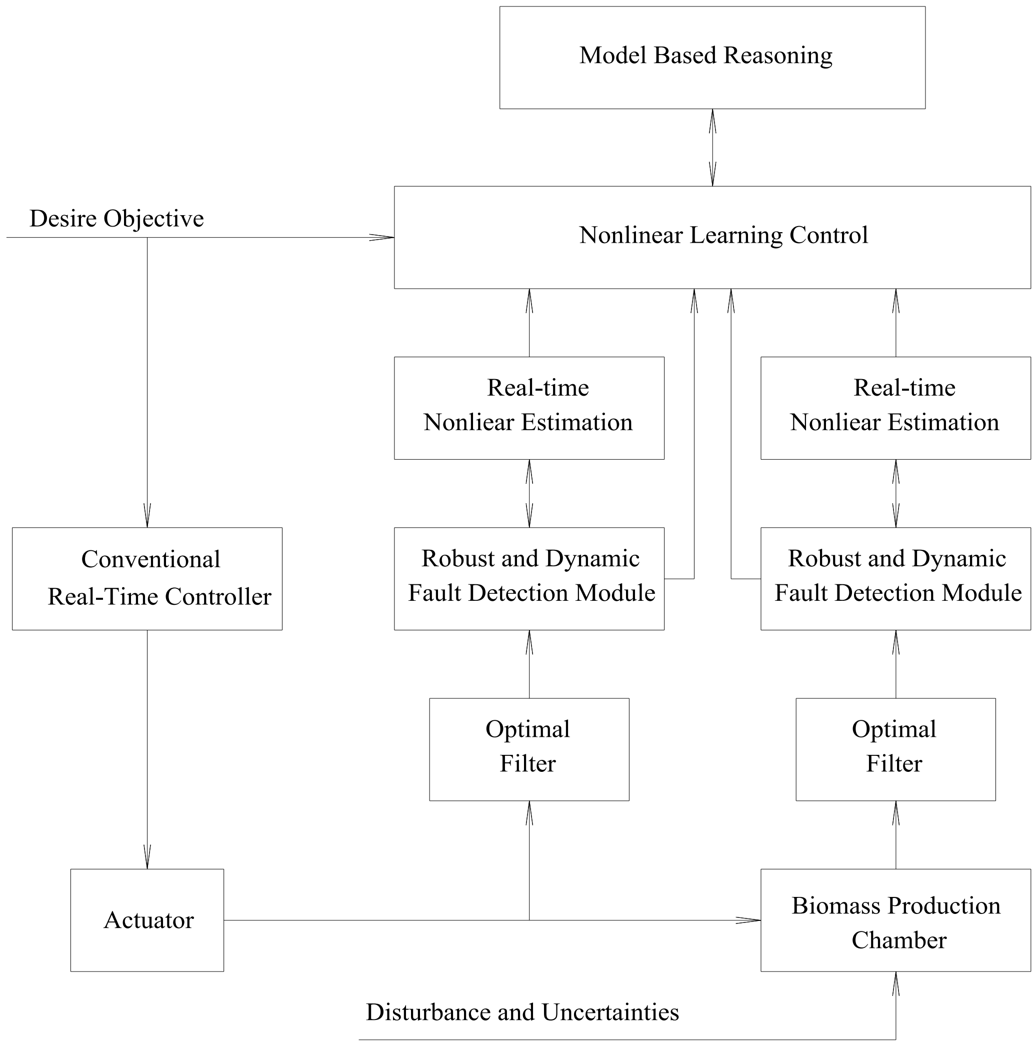

Figure 2: Control System Block Diagram

4. TRANSPORTATION AND STORAGE

4.1 Transportation

Transferring harvested fruits to the storage area is the final step and also an important task for the autonomous harvesting system. The transportation system should consist of actuation system that drives the conveyor belt. Electrical actuation system has more advantages over Pneumatic and Hydraulic system because of low pressure and less gravity conditions in the chamber. The ALSARAM arm will harvest the fruit and will place the harvested fruit on the transportation system, which will carry the fruit to the storage system.

4.2 Inspection

Inspection system is required to detect the damaged fruit or fruit with diseases, which can cause health problems to the astronaut. The inspection system should be placed online on transportation system that can detect the flaw before the fruit is stored.

4.3 Sorting and Packing

A sorting mechanism should be implemented that will sort varieties of fruit harvested. This might be useful for astronaut to easily identify the fruit they are looking for. A packing mechanism should be implemented before the storage section that will pack the harvested fruit. The packing system will preserve the fruit for longer periods of time.

4.4 Storage and Inventory

Normally Artificial refrigeration system is required to preserve the fruits but we can utilize the Mars natural environment for the refrigeration system. Using the natural environment of mars and implementing a temperature control unit it would be possible to maintain the temperature of the storage system.

A storage inventory system will be implemented in storage system that will maintain the fruit inventory. This system can be automated; if fruit available is less than the target inventory level then a signal for next harvesting cycle will be given.

Function	Description
Safety of fruit	No damage during transportation
Adaptable	It should adjust it self according to the type of fruit or vegetable to be harvested
Exit	Gentle drop to storage box
	Harmonize with storage box movement
Reliability	Fruit should not be stuck
Sorting	Fruit Sorting and storing should be automated online
Inspection	Damaged or fruit with diseases should be detected automatically
Cleaning	Cleaning inside the passage in case of emergency

Table 3 Functional Description of Transportation system

5. OVERALL CONTROL STRATEGY

5.1 Temperature

Polyurethane foam walls will serve as heat exchangers. Air circulation requires two 125W and two 150W blowers. The blower capacity is based on $246m^2$ of plant shelving. The air handling system provides from 3 to 4 air exchanges per minute, with air velocities ranging from 0.1 to 1.0 m/s. Heat rejection and humidity control will be accomplished by chilled water coils located at the blower's exits. The condensation that occurs on the coils will help to monitor the evaporation rates. Atomized streams of water implemented directly in the air stream provide supplemental humidification. The pathogen filtering system will be composed of electrostatic precipitators, which remove small debris, and coarse filters, which remove large debris to prevent contamination of air ducts.

5.2 Humidity

Humidity in the Mars BPC needs to be controlled and will be monitored by means of a Relative Humidity sensor, which when connected to a circuit provides on-chip signal conditioning. These sensors contain thermo set polymers that interact with platinum electrodes and allow an interchangeability of +5%RH, with stable performance. The sensor will be located in the BPC ceiling and it will operate in temperatures that range from 233.15 k to 358.15 K.

5.3 Pressure

Pressure will be measured and controlled by using a Sputtered Thin Film pressure sensor, which is stable even in extreme operating conditions. An Entran EXPT high temperature pressure sensor would be recommended. It has an operating range of 328.15 K to 523.15 K and a measuring range varying from 233.15 K to 423.15 K. The pressure sensors will be placed at the end of the air vents detecting air speed. If the air speed matches the desired speed, then no cleaning of the ducts is required.

5.4 Light

In order for the plants to receive natural sunlight, an Aerogel top round window has been chosen as the best option, because of the mass and power savings, which will allow maximum light of 400-700 nm transmittance and withstand the Martian ambient UV radiation as well as the other environmental parameters addressed above. Additionally, to ensure the appropriate functionality of the plants, artificial illumination will be feasible by using 400W high-pressure sodium lamps (6 per plant area), which yield an average photosynthetic photon flux of 1500 u.mol.m.s/msqds when operating at full power. The lamps are powered by dimming ballast, which allow variable light levels for each crop area, which are controlled by the chambers data acquisition recording and control system. The crop will be separated from the lamp bank by means of a polycarbonate plastic sheet barrier. Because the sodium lamps are pressurized, concern arises when transporting them in a cargo hold exposed to vacuum. This is why Light Emitting Diode (LED) banks will be implemented, since they are un-pressurized and can produce the necessary light for plant growth. LED's generate less heat and they are useful for longer missions, unlike incandescent and fluorescent bulbs.[5]

5.5 Atmospheric Gas

In order to maintain an effective plant production as well as plant waste processing, the level of atmospheric gases (oxygen and carbon dioxide) should be controlled. Therefore a system that can generate oxygen on demand, filter out carbon dioxide and replace or remove the nitrogen required. Replacement oxygen can be from two sources. First oxygen is a byproduct of photosynthesis, the plant produces certain amount of oxygen and crew uses some of that, then excess net gas can be separated using a commercial separator and stored for future use. Second method is oxygen generation involves separating elemental oxygen from bearing gases in the Martian atmosphere. This process is called as the Oxygen Generator System, which receives, compressed CO_2 and extract oxygen. CO_2 coming into the OGS from the mars Atmospheric Acquisition and

Compression system will be electrolyzed at a very high temperature (750 °C), causing oxygen ions to be stripped away from the carbon dioxide and will be filtered through crystal Zirconia. The O_2 would then be pumped along cylindrical tank used as storage unit. The storage unit would have pressure monitors to inform the computer whether or not it is full. If it is full then the computer overlooks the storage unit and O_2 would be transferred to another unit Plant will use CO_2, which will be needed to replenish occasionally. A simple sensor implementation based on CO_2 detection can be introduced. Once enough CO_2 has been pumped in, two air vents located laterally to the CO_2 "Pump tube" would turn on as result of the computer's instructions and spread the CO_2 uniformly throughout the BPC. [11]

5.6 Ventilation

Air velocity will dissipate the heat generated by the lighting systems. The surface temperature was assumed to be 400K and temperature of the air stream to be 293K. Nusselts number was evaluated for the velocities ranging from .10m/s to 5.00m/s. After calculations, a direct correlation between average coefficient of convection and velocity was found. Knowing the heat generated by the bulbs, an average convection coefficient can be calculated, yielding to an approximate velocity of 3.3 m/s.

Four vents located on 4 sections of the top edge of the BPC will be essential. Between two of the vents will reside the CO_2 intake system. Air ducts will run along the ceiling of the BPC starting from a main pump on the outside of the BPC and ending at each vent. At some point the vent will have to split into four ducts, which will run along the inside of the dome in circular fashion. The pressure systems will detect how much air travels through the ducts

5.7 Plant Growth Monitoring

The insertion of concept of Health Monitoring (HM) into existing automated monitoring and control systems will provide a real time intelligent, command and control system, which has the capability to monitor and observe transient behavior along with the dynamic parameters of the systems being tested. Current test capability cannot measure the dynamic behavior of System Under Test in real time. Abnormal dynamic properties are indicators of an out of tolerance performance of the SUT; they can be a predictor of impending failures in those systems. This feature adds a new dimension to existing test control mechanizations that will greatly enhance the accuracy of the "system state" which, in turn, increases the reliability of test and evaluation process over those currently in use. This attribute will speed up diagnostic analysis to seconds rather than minutes/hours, thus reducing significantly, fault detection and diagnosis. The system will periodically capture images of growing vegetation. By applying some image processing algorithms, we can approximate physical size, root length, and color histogram of the vegetation. With the periodic size monitoring, the growth rate can be calculated in both root and stem. We can also detect some plant irregularities such as disease by comparing the color histogram with the standard chart or model. [12]

The target set point and the overall top-level control scheme is as shown in the figure.

Parameter	Set Points
Temperature	10 to 30°C
Relative Humidity	40 to 90%
CO_2 Partial Pressure	0.1 to ~3 kPa
O_2 Partial Pressure	> 5 kPa
Light	400 to 700nm
Inert Gas Composition	Optional
Ethylene Gas	< 50 ppb equivalent at 100 kPa total pressure

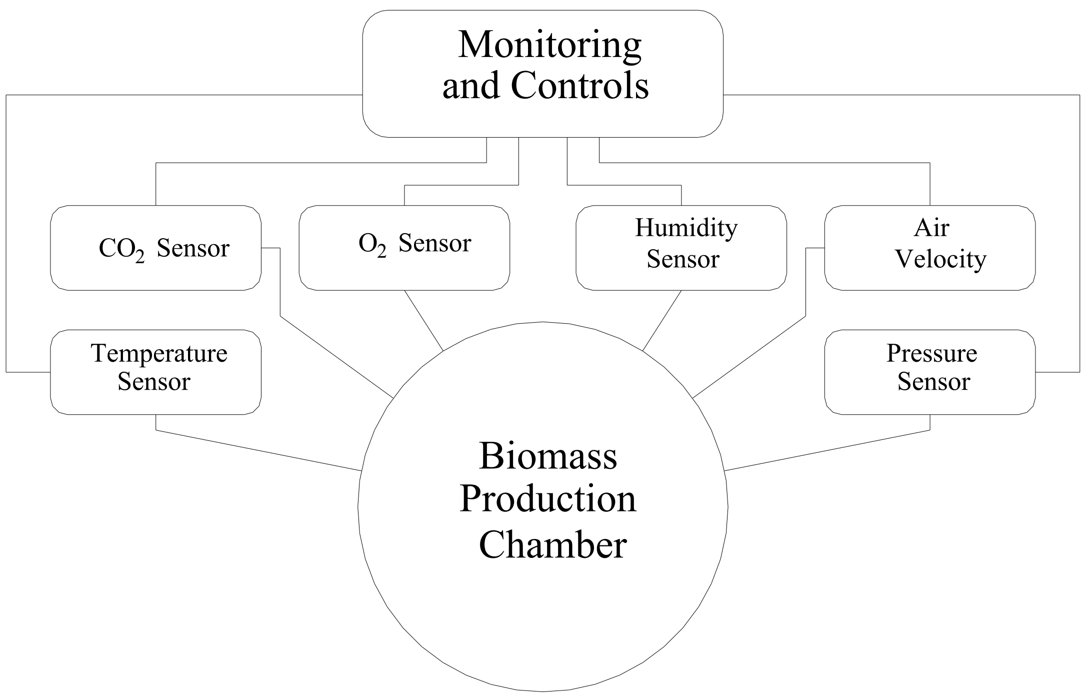

Figure 3 Overall top-level control scheme

6. CONCLUSIONS:

The innovative control framework provides autonomous operation of the robotic system in the BPC. The autonomous harvesting system and control strategy provides synchronization, which is suitable for a compromise between the device's complexity and its manipulative ability. Autonomous harvest robotic system and a biomass chamber will be a multi-tasking robotic system unit, which will harvest fruit, measure temperature, relative humidity, air speed, and light intensity with overall management and maintenance. This mechanism eliminates human intervention in BPC, avoiding contaminations and leakage of foreign elements, which allow consistent experimental procedure inside the chamber. More over such mechanism can reduce Psychological burden over the astronaut for harvesting and management. The study of such mechanism enhances our understanding of requirements for life support manipulation in the close test beds and it provides the baseline for space applications (i.e. International space station, Mars, etc)

REFERENCES

[1]Hoffman, S. J., and Kaplan, D. L. (1997) "Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team," Exploration Office, National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas, July, 1997. This is version 1.0. This document may be found on the Internet at:http://exploration.jsc.nasa.gov/explore/explore.htm

[2] Drysdale, A. E., Maxwell, S., Hanford, A. J., Ewert, M. K., (1999) Advanced Life Support Systems Modeling and Analysis Reference Missions Document. CTSD-ADV-383, JSC-39502

[3] J. Appelbaum, G.A. Landis and I. Sherman. "Solar Energy on Mars: Stationary Collectors" *Journal of Propulsion and Power, Vol. 11* No. 3, pp. 554-561. Available as *NASA TM-106321*.1993.

[4] Boynton William. *Mars Mercator Map of Neutron Levels*. Mars Odyssey Probe. University of Arizona. 2002

[5] Building Technologies Program. *Lighting Systems. Advanced Lighting Systems.* 1994 AnnualReport. **http://eande.lbl.gov/BTP/pub/annrep94/Lsals.html**

[6]Drysdale, A. E., Thomas, M. M., Fresa, M. C., and Wheeler, R. M. (1992). *OCAM - A CELSS Modeling Tool: Description and Results*. SAE Technical Paper 921241. Presented at the 22nd ICES

[7] Drysdale, A. E. and Grysikiewicz, M. (1996). MDSS-KSC Life Sciences Project Annual Report for 1995.

[8] Drysdale, A. E. and Hanford, A. J. (1999). *ALS SMAP Baseline Values and Assumptions Document*. JSC 39317. 6/18/99

[9] Dave Desrochers, Zhihua Qu, and Apiwat Saengdeejing, ``OCR Readability Study and Algorithms for Testing Partially Damaged Characters," 2001 International Symposium on Intelligent Multimedia, Video & Speech Processing, Hong Kong, May 2 - 4, 2001.

[10] Apiwat Saengdeejing, Zhihua Qu and David Huibregtse, ``Robust OCR System for Reading Optically Partially Damaged Characters," The 13th International Conference on Computer Applications in Industry and Engineering (CAINE-2000), pp.128-131, Honolulu, Hawaii, November 2000.

[11] Z.Qu, Robust Control of Nonlinear Uncertain Systems, John Wiley & Sons, Interscience Division, 1998.

[12] B.C.Williams, ``Model-based autonomous systems in the new millennium," Proceedings of AIPS-96, 1996