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IMPLEMENTATION OF SENSOR AND CONTROL DESIGNS FOR BIOREGENERATIVE SYSTEMS

UNIVERSITY OF FLORIDA

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The EGM 4000/4001 Engineering Design class is an interdisciplinary design course that allows students to experience the design process. The projects involved the design of sensors and subsystems of a closed-loop life support system (CLLSS) with special emphasis on the Controlled Ecological Life Support System (CELSS) currently being developed at Kennedy Space Center (KSC) by NASA. This year's class comprised students majoring in Engineering Science, Aerospace Engineering, Agricultural Engineering, Mechanical Engineering, and Computer and Information Sciences. Consequently, the projects received support from students with many different interests and areas of expertise.

To understand the work performed by the students, one must understand the purpose and concept of a CLLSS system. In the years to come, NASA will be constructing Moon bases and sending astronauts to other worlds on extended space missions. In order to support the crews, unreasonably large quantities of supplies would have to be sent from Earth. These supplies would be difficult to transport and require large holds. To remedy this problem, NASA plans to incorporate crops into the spacecraft. These crops would supply food for the crews, as well as provide beneficial psychological side effects. In addition, the plants would recycle the air and human waste and provide oxygen and water for the humans.

The students in the design class were to work on supporting this project. In order to do this successfully, the course was separated into two phases. The first semester involved studying the various aspects of a CLLSS to determine sensing needs and develop ideas. The second semester involved first determining which of the ideas were most promising. Specific sensors were then designed and tested under laboratory conditions with promising results. Finally, recommendations for further development were proposed.

CLLSS REQUIREMENTS

Since an operational CLLSS system would incorporate many different engineering and scientific disciplines, the class was divided into subgroups that would study the different areas of the system. The five areas of concentration were atmosphere and temperature control, nutrient delivery systems, plant health, plant propagation, and solids processing. The group investigating atmosphere and temperature control focused on the temperature distribution within the growth chamber as well as the possibility for sensing other parameters such as gas concentration, pressure, and humidity. The Nutrient Delivery Group investigated the sensing needs for monitoring the solution level in a porous membrane material and the requirements for measuring the mass flow rate in the delivery system. The Plant Health Group examined the causes and symptoms of plant disease and explored the various techniques for sensing these health indicators. The group investigating sensing needs for plant propagation and support focused on monitoring seed viability and measuring seed moisture content as well as defining the requirements for drying and storing the seeds. The Solids Processing Group covered the areas of harvesting, food processing, and resource recycling, with a main focus on the sensing possibilities for regulating the recycling process.

Atmosphere and Temperature Control

This group determined that one possible sensor is a relative humidity sensor that incorporates fiber optics. Another promising area is temperature or gas profiling of a growth chamber. This could provide needed information on the temperature gradients, as well as the gas flows within a chamber. This information would allow the determination of the ideal location for the various sensors that would be incorporated within the chamber.

Nutrient Delivery

This group found a crucial need for a wetness sensor that would determine the wetness of a porous medium on which the plants would be growing. This is an area of great importance since a saturated medium could cause the roots to rot, and a dry medium could destroy the plants. Consequently, a wetness sensor was proposed for semester two.

Plant Health

The sensing need found by this group was obviously a plant health sensor. Therefore, the majority of the work conducted was directed toward disease symptoms and available sensing technologies. The technologies studied included both destructive and nondestructive techniques including Mossbauer spectroscopy, fluorescence spectroscopy, visual imaging, nuclear magnetic resonance, and various others. Also, expert systems were studied to help control the sensor system to be developed.

Plant Propagation

This group studied seed quality testing, seed moisture sensing, seed drying, and seed storage. Quality is important in order to insure that the seeds will germinate. The moisture content is critical to prevent rotting of the stored seeds and growth of fungi. Seed drying and storage techniques must be developed to minimize damage to the seeds.

Resource Recycling

This group concentrated mainly on recycling the byproducts of a CLSS. This included harvesting, food processing, and waste recycling. The most promising projects were determined to be harvesting and food processing. These systems would need to be automated to relieve the crew from tedious work and allow them to concentrate on matters more directly associated with the mission.

CLSS DEVELOPMENT

Based on the studies conducted during the first semester, the class proposed various projects for development. These were rated and compared to determine which were most needed and feasible. This resulted in the selection of a seed moisture content sensor using infrared diffuse reflectance, a porous medium wetness sensor, a plant health sensor using infrared digital imaging, and a controlling system for a robot arm and the plant health sensor using neural networks.

Seed Moisture Content

Moisture content of soybean seeds was chosen as the property that could best be sensed for three reasons: (1) the test is nondestructive to the seeds; (2) the process of varying moisture content in the seeds for testing purposes is a simple procedure; and (3) the method is easily automated. A moisture content sensor is important in a CLSS for several applications. If the device could be constructed to sense the moisture of seeds or seed pods while they were still attached to the plant, the optimum harvest time may be determined. If not used to determine harvest time, a moisture content sensor could be used to determine whether a seed batch is retained for storage and replanting or sent to food processing, based on extremes in moisture content. Seeds too high in moisture may cause problems in storage as they are conducive to growth of mold and fungi and are more susceptible to mechanical damage during harvesting and handling. Seed batches of low-percent moisture may have dried on the plant too long, reducing their vigor and storage life. The measurement of seed moisture content may also be instrumental in controlling the drying times of seed batches before storage.

The concept of using infrared reflectance as a means to determine the moisture content of a seed batch is a technique based on the property of water to absorb certain wavelengths in the infrared spectrum. The band most widely used in on-line moisture determination is the 1.94-μm band within the infrared spectrum. Because light rays that interact with a rough surface are scattered, the best method of sensing absorption properties is by diffuse reflectance.

In the design of this sensor system, two filters must be used—one that passes a water absorption band and another that passes a reference wavelength. The passed wavelengths interact with the surface of the seed sample producing a reflectance inversely proportional to the amount of infrared energy absorbed. Collecting the reflected energy and focusing it on a detector produces a corresponding voltage output. The signal produced by the detector for each filter is recorded, and the ratio of the two reflectances is recorded. The two filters chosen were a 1.8-μm reference filter and a 1.94-μm bandpass filter. The detector type is lead sulfide, which is capable of detecting both wavelengths of interest for the system.

Seed batches of 250 g were prepared for testing. Oven drying, microwaving, and sun baking created seed samples of relatively low moisture content (approximately 6%). To obtain high moisture contents, seed batches were soaked in liquid water for different time intervals to achieve samples ranging from 20-35% moisture. The moisture content of each 250-g batch was then measured by a Burrows Model 700 digital moisture meter and the values were used as the basis for test validation. The final tests performed under the optimal conditions resulted in reflectance measurements of seed samples that successfully differentiated between batches of different moisture contents.

Porous Medium Wetness

In order to maintain an efficient nutrient delivery system in a CLSS, the ability to monitor the amount of nutrient solution available to a plant through the porous medium is necessary. The most important factor in plant growth and productivity is soil water, which controls the uptake of most of the nutrients required for plant growth. Nutrient uptake of a crop varies throughout the crop season, as well as daily. Monitoring the wetness of the porous plate will provide data necessary to help control the amount of nutrient solution available to the plants throughout their growth cycle. This control can help to maintain healthy plants, prevent leakage to the CLSS atmosphere due to excess solution in the medium, and prevent air from entering into the delivery system due to a lack of solution in the medium.

The degree of wetness pertains to the relative concentration of water in a porous body, independent of the body size. Two sensing methods were developed for monitoring the wetness of the porous medium; one that uses infrared reflectance and one based on heat dissipation. The infrared technique is similar to the approach used by the Seed Moisture Content Group. This technique is especially suited to sensing porous plate wetness since it measures surface moisture. The thermal technique was developed to exploit the fact that the thermal properties of water differ quite significantly from those of air or ceramics. The technique of measuring heat dissipation to sense the degree of wetness in the porous medium is based on the fact that the rate of heat dissipation in a porous medium of low conductivity is sensitive to water content. As the water decreases, a larger temperature gradient is needed to dissipate a given quantity of heat. The wetness of the porous medium can be correlated with the temperature gradients measured by the sensor for a given heat dissipation. These techniques allowed the wetness trend within the plates to be determined, though the exact moisture content was not quantified.

Plant Health Sensing

In order to maintain an extended space mission, it may be necessary to grow crops to support the astronauts physically and psychologically. The plants should be grown efficiently, with minimal interaction with the crew. This requires a number of automated systems to care for the crops. One such system should be able to monitor the health of the plants. This could be accomplished using three different levels. The first of these levels would consist of a primary health sensor that could scan the entire crop in order to identify trouble areas. The secondary sensor would be able to examine a trouble area more in-depth to specify the location and extent of damage. Finally, the tertiary system would be able to analyze the trouble area for a specific cause and a possible solution for the problem. The primary and secondary sensors would be noninvasive, while the tertiary sensor may be destructive; however, the extent of the destruction could be minimized by the information gathered by the secondary system.

This project centers upon the design and fabrication of a primary sensor system. To sense the plant health, various factors may be examined. In this case, the amount of chlorophyll located in the plant tissue provided a direct correlation to plant health. It may be seen that health decreases as the chlorophyll concentration decreases. This may be readily seen in chlorotic and necrotic tissue. Chlorotic tissue shows a deficiency in chlorophyll through a yellowing of the tissue. Necrotic tissue is dead tissue, which is brown and dry in appearance.

Chlorophyll is detected through the use of IR radiation absorption. Absorption is measured through the use of a digitizing camera system. Light is reflected off the leaf and collected by the camera. The light is first passed through a bandpass filter in order to pass a wavelength of 671 nm, which corresponds to the peak absorption of ***chlorophyll-a***. As the amount of chlorophyll decreases, the amount of 671-nm light reflected will increase. This will be observed by the camera and recorded by a computer within an array of integers. This array represents the light intensities located within an image. Each number in the array represents a grey level and as the numbers increase, the intensity of light increases. Using the 671-nm filter to analyze the chlorophyll content of the plant tissue, it was possible to obtain data that clearly displayed unhealthy regions on the leaf.

Neural Networks

The main purpose of this project is to try to adapt neural network theory to CLLSS applications, or more specifically, to plant health. In order to do this, sequential programs are used to simulate the parallel distributed processing of a neural network. This project was separated into two phases. The first consisted of using neural networks to control a robot arm. The second consisted of using neural networks to determine the health status of a plant based on the data accumulated by the Plant Health Group.

The robot arm was to be trained to grasp an object. This object was assumed to be the stem of a soybean plant approximately 2 in above the growing surface. The first preliminary step was to design and train a network to transform two-dimensional Cartesian coordinates to polar coordinates. Networks for polar-to-Cartesian coordinate transformations were also developed. Therefore, coordinates could be entered in either form. The team found that by giving the network more information by increasing the number of input elements, the network's ability to generalize was enhanced.

Phase two of the project involved using neural network techniques to determine the state of health of a plant leaf in an automated fashion. The goal was to develop a program that would read in a file containing data on the infrared reflectance of a leaf and prepare the data for use by a neural network that would be trained to distinguish between a healthy and a sick leaf. Although the neural network was trained on a very limited number of unhealthy conditions, the purpose was to demonstrate the feasibility of the process.

The Plant Health Group provided 28 usable images. All the images were taken in one sitting, so the lighting intensity was constant. Twelve of the leaves appeared healthy, and 16 appeared unhealthy. The Plant Health Group looked at a color graphic computer display of each leaf that was consistent with the leaf's visual appearance. One of the apparently healthy leaves, however, showed a spot of some kind and was thus graded as suspicious. Arbitrary values were then assigned to each category of leaf. Healthy leaves were assigned 0.9, and unhealthy leaves were assigned 0.1. The suspicious leaf was not assigned a value. A training set was created, consisting of 8 healthy leaves and 12 unhealthy ones. The other eight leaves, including the suspicious one, were saved for testing. After training, the network output values were within about 0.001 of the expected values for the training set.

For the test set, every leaf, except for two, was graded by the network to within 0.017 of the expected value based on visual classification. Of the other two, one which had been visually graded unhealthy was graded by the network at 0.761 and thus labeled suspicious. Visually, this leaf was healthy looking except for a brown edge. The other leaf, which had been visually classified as suspicious, was assigned a value of 0.898 by the network, which was considered reasonable.

CONCLUSION

In conclusion, all the design projects were at least partially successful in producing a working prototype. Further work is recommended as follows: The Seed Moisture Content Group recommends that the system developed should be interfaced with a computer and integrated with fiber optic technology to further enhance the system. Also, infrared-light-emitting diodes could be used in order to eliminate the need for fragile filters. Currently, several members of the Porous Medium Wetness Group are designing a self-contained unit that will be flown on a KC-135 microgravity flight to further test the sensor. The Plant Health Group recommends continued development of the project by incorporating three-dimensional analysis and background distinction into the health sensor. Neural networks could be designed to distinguish the edge effects and the three-dimensional problems of visual imaging.