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**ROBOTICS IN A CONTROLLED, ECOLOGICAL LIFE SUPPORT SYSTEM**

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## **ROBOTICS IN A CONTROLLED, ECOLOGICAL LIFE SUPPORT SYSTEM**

### **ABSTRACT**

Controlled, Ecological Life Support Systems (CELSS) that utilize plants to provide food, water and oxygen could consume considerable amounts of labor unless crop production, recovery and processing are automated. Robotic manipulators equipped with special end-effectors and programmed to perform the sensing and materials handling tasks would minimize the amount of astronaut labor required.

The Human Rated Test Facility (HRTF) planned for Johnson Space Center could discover and demonstrate techniques of crop production which can be reliably integrated with machinery to minimize labor requirements. Before the physical components (shelves, lighting fixtures, etc.) can be selected, a systems analysis must be performed to determine which alternative processes should be followed and how the materials handling tasks should be automated.

Given that the current procedures used to grow crops in a CELSS may not be the best methods to automate, then what are the alternatives? How may plants be grown, harvested, processed for food, and the inedible components recycled? What commercial technologies current exist? What research efforts are underway to develop new technologies which might satisfy the need for automation in a CELSS? The answers to these questions should prove enlightening and provide some of the information necessary to perform the systems analysis.

The planting, culturing, gathering, threshing and separation, food processing, and recovery of inedible portions of wheat were studied. The basic biological and materials handling processes of each task are defined and discussed. Current practices at Johnson Space Center and other NASA centers are described and compared to common production practices in the plant production industry. Technologies currently being researched which might be applicable are identified and illustrated. Finally, based on this knowledge, several scenarios are proposed for automating the tasks for wheat.

Hetzroni, *et al.* (1992) used a machine vision and image processing system to monitor the nutrition and health of lettuce grown in a controlled environment chamber. Neural networks were used to classify picture elements (pixels) into normal or nutrient-deficient classes. Miles (1989; 1991) showed that image processing could detect patterns in wheat leaves caused by nitrogen, iron and/or potassium deficiencies.

The ROTRAN® 2000<sup>1</sup> robotic transplanter for bedding plants uses an integrated machine vision and image processing system to check for seedlings and to direct the robot to correct for misses (Beam, *et al.*, 1991). This is one of the few commercially available machines which has the versatility required of a CELSS.

Benady, *et al.*, 1992 utilized an electronic sensor for ethylene to determine ripeness of cantaloupes. The aromatic volatile gases emitted naturally from climacteric fruit during ripening are detectable by the small, hand-held SnO<sub>2</sub> sensor. The ability to accurately measure crop ripeness is necessary for selective harvesting, and for automating a CELSS.

### *Manipulators and End-effectors*

Robot manipulators may be Cartesian, revolute, or hybrid combinations depending on the physical location of the servomechanisms. In Cartesian style robots, the actuators are positioned so that each axis provides linear motion for a carriage that carries the next axis, or the end-effector. Curvilinear motion is provided by coordinating the relative motion between each axis. In revolute robots, the manipulator consists of a base and arm sections with servos at each joint to provide rotary motion. By coordinating the motions between each servo, linear motions of the end-effector can be achieved. Cartesian-axes and revolute-joints may be combined to produce a wide variety of robot types.

End-effectors, or grippers provide the mechanisms to grasp objects. Many end-effectors also have axes or joints, which permit objects to be positioned or oriented independently of translocation by the manipulator. The physical design and size of grippers depends on the objects to be grasped, and may be unique for each task. Simonton (1991) has developed end-effectors for manipulating plant materials.

Because the robot(s) will be required to perform a multitude of tasks, the end-effectors must be automatically changeable, without human assistance. This capability is not normally found on industrial robots and may require considerable development efforts for the unique set of CELSS end-effectors. The connections to the end-effector must include:

- physical support,
- electrical, pneumatic, vacuum, and/or hydraulic service, as well as
- sensor and control lines.

### Transplanting

Kutz, *et al.* 1987 demonstrated robotic transplanting of bedding plants from a seedling flat to a grow flat (Miles and Kutz, 1991). The gripper was two flat pieces of spring steel that open and closed pneumatically around the seedling plug. The Puma robot inserted the gripper into each cell by following an "L" shaped approach path which kept

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<sup>1</sup>ROTRAN 2000 is a registered trademark of Robotic Solutions, Inc., 1291-G Cumberland Avenue, West Lafayette, IN 47906.

the seedlings from being bent and broken during the downward motion. The seedlings were inserted in a previously dibbled hole in the grow flat soil mix, and released by opening the grippers.

Beam, *et al.*, 1991, developed a Cartesian type of robotic transplanter which uses a similar gripper, but employs different technologies for automating and coordinating motions of the twin gantries and the conveyors which position the flats. Pneumatics are used for positioning the gripper vertically and for opening the fingers, while stepper-motors are used to position the gantry carriages laterally, and to position the flats on the conveyors. Because all the motions are controlled by a microcomputer, ROTRAN® 2000 is capable of transplanting from a wide variety of flat types and sizes, at a rate of approximately 2000 seedlings per hour.

### Melon Harvesting

Selective harvesting of cantaloupes is being accomplished by a Cartesian robot designed by engineers at Purdue University and the Agricultural Engineering Research Institute, Agricultural Research Organization (Volcani Center), Bet Dagan, Israel (Edan and Miles, 1991; Edan, *et al.*, 1991; Benady, *et al.*, 1991). The 3 axes position the ring grippers over the fruit, and match the ground speed of the vehicle while the gripper descends and grasps each melon. After the rings close around the melon and the manipulator lifts it a short distance, a swinging knife trims the vine. Because the manipulator picks each fruit individually and the machine vision and image processing system and the "sniffer" sensors detect fruit ripeness, multiple and selective harvests are possible with this robot.

### *Animated Simulation/Systems Engineering*

Because of the versatility of programmable machines and the complexity of tasks, a myriad of scenarios are possible when automating crop production. When harvesting a row, or tree, are differences in performance from one test to another due to changes made in the machine, or differences in physical properties of the crop? In agriculture, it's not uncommon for threshing efficiency to change by 30% or more due to changes in the physical properties of wheat, with no changes in combine settings. Such uncertainties could lead to endless experimental research. A preferred approach would be to develop 3-D, animated models of robots which could be used to simulate materials handling and quantify responses for changes in environmental conditions and the machine design. This approach would permit the affects of changes in design of the machine to be clearly separated from crop parameters. In addition, solutions are much quicker to obtain, and answers can be obtained at any time, not just when the crop is ready.

The animated simulation approach clearly defines the work space and time requirements to perform a task. This information determines some critical design parameters for the robot, namely the size or length of each axis, and the sizes of servos required to move the materials along each axis in the allocated time period. With this information, the design engineer will be able to make better decisions concerning the robot hardware and software specifications.

The modeling and simulation approach does not eliminate the need for laboratory studies to validate the results. Tests must be performed to confirm that the grippers and

## AUTOMATED WHEAT PRODUCTION IN A CELSS

Because the potential scenarios for a CELSS are so complex and varied, it is almost impossible to conceptualize automation scenarios without considering a specific example first. By studying how wheat may be grown in a CELSS, it is hoped that the general requirements for automation will become evident.

### **Planting**

Planting is the process of transporting seed or propagule from the storage area, opening the container, and placing the seed in the desired location, at the proper depth, orientation and spacing.

### *Process Model*

The prime requirement of planting is to ensure that the seed or propagule is in contact with the soil, or wicking apparatus, that provides adequate exchange of essential nutrients, primarily oxygen and water. During the germination process, the seed swells as it imbibes water, absorbs oxygen, and respire  $\text{CO}_2$ . Germination also requires darkness and a proper range of temperatures.

### *Current Practices*

Hydroponics and nutrient film techniques have been devised for growing plants in a CELSS. At JSC nutrients are circulated through trays which have fiberglass wicks inserted in rows. Imbibed wheat seeds are sown in the rows between adjacent wicks. As the seeds germinate, roots extend down into the tray and form a mat that absorb the essential nutrients from the liquid solution. By imbibing the seed, more uniform stands can be established, but since soaking softens the seed coat, this technique requires much easier handling to avoid damaging the emerging tissues.

Minnesota basalts have been ground to particle size distributions which simulate lunar soils, and used as media for growing plants. In this process, the lunar simulant is spread evenly across trays through which water with added nutrients is pumped. Seeds are planted directly in the simulant.

Dreschel, *et al.*, 1988 have devised a method of circulating nutrient solutions in porous tubes under slight vacuum to prevent dripping. Seeds or seedlings are placed on the tube, and wrapped with black plastic sheath to shield the roots from light. A plastic tube cut along its length is placed over the plastic to hold it and the roots against the porous, nutrient supply tube. The roots wick the nutrients from the solution by capillary action across the porous tube.

In a demonstration of a commercial robot's capability, Boeing personnel at Kennedy Space Center (Parker and Eckhoff, 1989), equipped a robot with a suction tip end-effector, and programmed it to dip the tip into a canister of seed, then when a seed had plugged the suction hole, transport the seed over to a seed tray. While this scenario results in the simplest end-effector, it is very slow. A multiple-tip end effector would seed the flat much faster (del Castillo, 1987), but adds complexity and mass to the design.

Commercially, wheat is usually seeded with drills with disc openers about 7 inches apart. For seeding rates of 1 bushel per acre and seed counts of approximately 15,000 per

lb., the within drill spacing should be about 1 seed per drill-inch. A crop similar to wheat, rice is usually transplanted. Rice seedlings are started by germinating the seeds in a flat without cells. Workers or machines then pinch plugs out of the mat of roots and shoots and place each one individually into the soil. Often, rice is transplanted directly into puddled soil and flooded with water.

In the bedding plant industry, a considerable amount of automation has been developed (Chen *et al.*, 1992; Gautz and Wong, 1992; Honami, *et al.*, 1992; Kondo, *et al.*, 1992; Mohapatra, *et al.*, 1992; Morimoto, *et al.*, 1992; Nambu and Tanimura, 1992; Onoda, *et al.*, 1992; Roberts and Swanekamp, 1992; Sakaue, 1992; Shaw, 1993; Suggs, *et al.*, 1992; Tanaka, 1992). Customary practices include sowing seeds into flats with many small cells filled with a light-weight soil mix, and transplanting the seedlings into a grow-flat where the plants continue to grow. By germinating seeds in small cells, better control of environmental conditions is possible and this leads to healthier plants and a higher percentage of germination. Because the seedling flat cells are 10% the size of the grow flat, transplanting frees up some greenhouse space for a few days. Since 100% germination is practically impossible to obtain, even with selected seed, the seed flats often have 20% misses or more. During the transplanting operation, these empty cells are skipped, and the grow flats 100% populated. By transplanting, the growth chamber, or greenhouse space is better utilized.

Seeding is often accomplished with a rotating, perforated drum on which a vacuum is pulled. The drum constitutes the bottom or side of a seed hopper, and by rotating upwards, seed are sucked against the tiny holes and carried up and out of the hopper. On the opposite side, the seed are released into tubes which route them to a row of cells in the flat. The drum rotation and flat advancement are coordinated so that one seed is placed in each cell. Usually the seed are then covered with a small amount of vermiculite or soil mix. Because the seed are dropped, they often roll to the corners of cells, which make them difficult to transplant mechanically.

Because each plant species has unique requirements for root and canopy environments, a myriad of seed flats and grow flats have been developed by commercial growers. The size, shape, depth, density and pattern of cells vary greatly. Some are in neat rows and columns, others are arranged to facilitate movement of air in the root zone and canopy. Because of this diversity, automation of a full range of tray configurations has not been possible until the introduction of robotic transplanters such as ROTRAN® 2000.

### *Proposed Automation*

The tasks of transporting the seed from storage, opening the container, singulating the seed, and placing the seed in the growth media at the proper spacing, depth, and orientation can be automated by a number of suggestions.

### Pencil Seeder

One possibility is to develop a storage container which also performs the singulation task, and which can be grasped by the end-effector and positioned by the robot to the proper locations for planting each seed directly in each grow-flat. The robot would supply the power (pneumatic, vacuum, or electric) required to operate the singulation

mechanisms. This device is envisioned as a large pencil, in which the barrel holds the seed, and the point of the pen is used to hold the individual seed and place them into the proper places in the grow-flat. The singulation might be accomplished by a ball-point pen type of mechanism. A push on the top of the pen would cause the device to acquire another seed from the barrel, and leave it on the tip ready for insertion into the lunar simulant, or placement on a wick. The pencil seeder has several attractive aspects:

- Planting the seed in the same container used for storage eliminates a materials handling task and simplifies the process of seeding;
- The pencil seeder can be quickly adapted to any type of robot;
- In case of robot failure, the pencil seeder becomes a tool used by an astronaut to mechanize planting and to reduce the labor requirements; and
- The pencil seeder has considerable commercial spin-off for small farmers, especially producers of specialty crops where seed quantities are small and seed prices often reach several thousand dollars per pound. The pencil seeder actually favors the small business because it handles the small quantities required in a CELSS.

### Seed Tapes

Tapes in which seeds are placed at the proper intervals could be considered for automating the seeding process. The seed tape would be stored until needed, then the proper amount unrolled and placed on the growth chamber trays. This would require the robot to spool and cut the tape to the proper length for each row. End-effectors to accomplish this task would be simple and easy to design. The tape would be made of a wicking material that provides the proper flow of nutrients to the germinating seed. For missions where all the seed are supplied from Earth, the material could be bio-degradable. Eventually, the material needs to be reusable, or if biodegradable, made from plant materials generated as a by-product, such as rice, cotton, or linen fiber mats. The features of this technology are:

- The end-effector mechanisms to spool and cut the ribbon are simple and easy to design;
- Commercial technology already exists to place seed into seed-tapes prior to a mission; and
- The technology could be readily adapted for manual use if the robot fails;

### Gels or Foams

Seed could be prepackaged with dehydrated gels or foaming agents in containers similar to tubes of caulk which can be squeezed, or pushed. By injecting water several hours prior to planting, the seed could be pre-germinated. After adding water, the tubes would need to be stirred, or rotated to insure uniform distribution of seeds in the gel. The robot would grasp the tube, and move it across the trays, depositing the correct amount of gel or foam. For some, high-density applications, the robot might lay down a continuous bead of gel, while in other cases, the seed would be placed in hills or squirts. The plant

population would be determined by the statistical density of seeds in the gel, and the volume of gel applied, and the positioning of the robot manipulator. Foams are mentioned with gels because the carrier material must provide not only liquid nutrients, but for rapid exchange of carbon dioxide and oxygen as well. This approach has several attractive features:

- Gels are a commercial method of planting high-value seeds and much of the technology is readily adaptable;
- The sensing and controls required for robotic application of glue and weather-stripping have already been worked out and can be quickly adapted for this use;
- In case of robotic failure, an astronaut could wield a "caulking-gun" filled with a tube of gel seeds;
- Seed are stored in the application container, saving a materials handling step;
- The knowledge gained by researching the nutrient transfer characteristics of gels and foams would have immediate impact in commercial gel products; and
- This approach to seeding could also be marketed to small, family producers of high-valued seed crops.

### Seed-Flats and Transplanting

In order to optimize the use of the growth chamber, seeds could be planted into seed flats with small cells, then transplanted into pots or grow-flats after the seedlings have outgrown the seed-flats. For the germination and seedling growth stages, the seed flats would occupy about 10% of the space required by the fully-grown plants. For a few weeks at least, the seed-flat or transplanting approach would make growth chamber space available for other crops. The technologies required to place the seed into the seed-flats could be any of the above-mentioned ones, including the commercial, drum-style. In this case, the seed-flat would be brought to a stationary seeder, instead of taking the seed to the grow-flat located in the chamber.

Once the seedlings have filled out the space available in the seed-flats, they can be transplanted to the grow flats or pots. During the transplanting process, inferior seedlings can be removed, thus only the best plants would occupy space in the grow-flats. Grading could be based on superior growth rates, leaf areas, stem diameters, etc. The need to do this comes from the requirement to make optimum utilization of space in the growth chamber. Because of genetic variation even within a cultivated variety, individual plants may have several times the productivity of "average" plants. As a result, this technique could significantly increase yields.

The seed-flats should be constructed of porous materials which enable nutrients to flow freely to the seed. New designs will be required since commercially-available, plastic flats are practically impermeable to liquid and air flow, and rely on a drain hole in the bottom of each cell. The seed and grow flats proposed here would be made of fiber-glass, or porous plastic material that wick nutrients from beneath the flat, and provide adequate air exchange. The seed and grow flats would sit in nutrient delivery trays through which liquid media and oxygen are pumped. Control of the nutrient delivery system would



provide for ebb and flow to prevent saturation or drowning of roots. The soil media used in the seed flat should be finer than the grow flat, and can be made from decomposed plant materials, or lunar or Martian materials.

The seed-flat or transplanting method has a number of salient features:

- Seedlings grow better in smaller, confined cells provided by the seed flat;
- Less space is consumed during the juvenile stages of growth, thereby freeing chamber shelf space for other crops;
- The seeding process can occur in a single location, with the seed-flats transported to the growth chamber; (Designing machinery to automate seeding may be much easier.);
- Higher crop productivities are likely because of plant selection during transplanting;
- Transplanting can occur into pots, making it possible to place plants or clumps of plants individually; Plants requiring higher light intensities could be placed where such conditions occur. Plants requiring low light levels could be placed on the edges, or sides away from the light. This could lead to inter cropping, and substantial increases in food productivity without increasing the chamber size;
- These technologies could pave the way for improving performance, lowering costs and raising profits of commercial greenhouse producers of plants. The potential for commercial spin-offs in the plant cell culture industry is highly significant.

## **Culture**

The efficient production of wheat in an environmental chamber requires control of the nutrient supply and exchange rates. The level of nutrients must be between minimum required for growth but less than toxic concentrations. Environmental variables, such as temperature, humidity, radiation, and nutrient pH must be such that the rate of basic physiological processes is satisfactory to sustain growth and development of plant tissues. Since the processes are complex and dynamic, the model must consist of a set of numerical equations describing the rates of material transfer as functions of physiological states and environmental conditions. As much as possible, the equations should be cause and effect models, to permit them to be used to predict responses for future conditions.

Numerous researchers have collected data on wheat growth in controlled environment chambers and developed models of the results. Work by J. T. Ritchie and S. Otter (1985, and 1987) has resulted in the CERES-Wheat model. Recently, Canpolat and Bolte (1993) converted CERES-Wheat into an object-oriented model that facilitates updates and changes, and makes it more usable as a management tool. Salisbury and Bugbee (1988a,b; 1989; 1991) showed that the potential production is far greater than record yields achieved in the field. Volk and Cullingford (1989) and Volk and Rummel (1987) developed BLSS, a model of wheat that tracks the flow of carbon, hydrogen, oxygen and nitrogen through the complete processes of a CELSS.

## ***Current Practices***

Wheat has been grown hydroponically in environmental chambers at Kennedy and Johnson Space Centers. In each case, seed are pre-soaked, then placed on wicks which supply nutrients from a liquid solution pumped into the trays beneath the wicks. The seeds germinate, and the roots extend into the tray, forming a mat which take-up nutrients and water. By the end of the growing season, the roots have filled the entire rooting zone. Wheat has also been grown on the porous tubes developed at KSC.

Wheat is grown in controlled environments only for research purposes due to the considerable cost difference over field practices. As a result, there is little mechanization of a scale suitable for a CELSS. However, practices developed for other crops may be adaptable.

Because lighting is a large energy cost and radiation not absorbed by plant leaves is wasted, relocating and spreading of plants is a common practice in greenhouses. Plants grown in pots are moved apart as the leaf area increases to absorb additional radiation. In some commercial facilities for lettuce, plants are grown in trays that move progressively apart as the plants mature. Previously proposed scenarios for CELSS would have a system of conveyor-tables which moves every few minutes to expose all the plants to the same amount of light and the same photo period. In a simple system, where the return conveyor is beneath the illuminated tables, the lights would stay on 24 hours per day, but each plant would receive only 12 hours of light, unless a supplemental bank of lamps were placed beneath the top conveyor to shine on the bottom tables. The motion of the plants would also dampen out spatial differences in light intensity. All such systems seek to have leaves intercept 100% of the light.

Another concern for illumination is the peak energy consumption. By adjusting the timing of the light period for each shelf, the peak can be greatly reduced. For an 8 hour photo period, the peak would be 1/3, and for a 12 hour period, the peak would be 1/2. For photo periods greater than 12 hours, the peak would be the same, but the area (power or wattage) would be reduced.

#### *Proposed Automation*

The one approach that appears to provide the versatility in environmental conditions required for the CELSS-candidate crops is ebb and flow tables with pots and/or flats. The volume of each pot must accommodate the root mass at plant maturity. The top surface of the pot must be as small as possible, to permit plants when small to be close enough to intercept the maximum amount of light. Then, as the plant leaf area enlarges, the pots can be spaced apart. The pot would rest on ribs or fingers formed in the bottom of the table, to facilitate drainage and air exchange. The nutrient solution would be pumped onto the table to a predetermined level that permitted the soil or wicks in the pots to saturate and wet the plant roots. Then the nutrient solution would be drained from the table, which would permit air to replace the liquid in the soil mix or wicks, much like natural, field conditions. Thus, the name ebb and flow. Although there are suggestions that hydroponics techniques are more efficient in carbon utilization than soil techniques, there is no reason that if provided similar rates of nutrient flow to the roots, that one system would grow a root to shoot ratio different from the other. The root mass (carbon) typically tied-up in a soil mixture can be extracted from an inert simulant or lunar soil by supersaturating it and developing a fluidized bed (quicksand), then lifting the plant by its

shoot. Once the plant was extracted from the pot, the soil mix could be dumped, washed, and reprocessed for the next crop. The ebb and flow technique should air-prune the roots (Huang and Ai, 1992; Chun and Takakura, 1992), and cause less root entanglement with the soil particles. But if not, then the soil can be recovered by oxidizing the root mass, which would also recover carbon and other nutrients. This would obviously be much simpler to automate than hydroponics which requires wicks to be cleaned and reprocessed between crops.

This approach would require that carriers be developed to transport the pots from the central processing station to each growth chamber table. The carriers would be held by a revolute-joint robot that moves along a rail in each chamber. At the airlocks between chambers, the robot would secure the carrier, and then affix itself to a special joint in the next chamber, which would permit it to be powered as it detached itself from one rail and attached to the rail in the next chamber. This capability would permit the robot to move along rails, yet cross obstacles such as airlocks and doorways. And, it would permit the robot power leads to be the length of one rail (probably one chamber long). The same procedure would be followed when going from one level in a chamber to another. The rail would be suspended from the "ceiling" in each chamber. This robot would have a number of end-effectors which permit it to grasp different objects and perform the required tasks. For example, when spacing the pots in the ebb and flow tables, the robot would traverse the rail until coming to the bay requiring the plants to be spaced. Then it would reach out and grasp each pot to be removed and place them in a carrier. When the required number of plants have been moved, the robot would move each remaining plant to the desired place on the table, according to predetermined patterns. The plants removed from this bay would be transported to other locations in the growth chamber and positioned correctly on tables by the robot.

Although the scenario described above refers to stationary tables, there are advantages to moving them along a conveyor, to pass beneath a bank of lights, and various stations where the required tasks are accomplished. Vertical lifts at each end of the sliding (conveyor) shelf would transfer the rectangular table from one level to another. The advantage of this system would be to minimize the number of lights required, but at the cost of additional hardware to move the tables of plants. Usually, systems which do not require motion are more reliable and require less maintenance. Since a robot carrier will be necessary to transport materials to and from the preparation and processing areas, letting it also provide the movement of plants will reduce the complexity, size and expense of the growth chamber. And, it is not likely that the launch weight of the extra automation mechanisms for the conveyor tables would be less than the weight of the lights required to illuminate all the growth chamber shelf space.

However, a single moving conveyor would bring all the plants past a workstation at the end, thereby alleviate the need for an aisle, and make the growth chamber more efficient. In a cylindrical chamber, the shelves could rotate on a conveyor which moves around the axis of the chamber. The workstation or aisle space would be in the center and the shelves rotate around it. The lighting would be around the inside wall of the chamber. The aisle floor would block out light from the plants beneath it, creating a dark or night period. The height of the floor would be such that the plants receive up to 16 hours of light per day, with 1 revolution of the shelves per day. The ideal width of the shelf must

be determined from light interception models. It's possible that two or more conveyors could rotate concentrically, with plant species requiring lower light intensities on the inside. In either case, the shelves would be populated with plants in pots.

The potted plant approach has a number of desirable features:

- Multiple robots could perform simultaneous tasks, or be held in reserve in case of failure of the primary unit;
- By using pots, the seeding, transplanting, harvesting, and recycling of pot materials would occur in a central work station, thereby simplifying the mechanization of materials handling;
- The energy efficiency would increase because pots can be easily spaced further apart when the plants grow large;
- Pots facilitate inter cropping which would accommodate variances in environmental conditions, particularly light intensity; and
- In case of failures, single pots can be replaced rather than entire trays, and the production quickly return to normal capacity.

### Gathering (Harvesting)

As wheat matures in the field, it dries and turns a golden brown, due to physiological aging, and to stresses imposed by high temperatures and late Spring droughts. In some situations, wheat and rice are cut and left to dry for a few days before combines (combined harvesters and threshers) are used. This decreases the energy required to thresh and separate the grain. In the growth chambers, drying can be accelerated by withholding the nutrient solution, decreasing ambient humidity, and elevating air temperature.

The optimum time of harvest is a tradeoff between grain moisture content and the need to plant the next crop. The grain must be below 14% to minimize the risk of molds and to store well for up to 12 months (Brooker, *et al.*, 1992), but if allowed to dry in the chamber to 14% or less, the kernels shatter easily, leading to serious pre harvest and gathering losses, and possibly increasing damage to the grain during threshing. The optimum grain moisture content to minimize gathering losses is about 18%. Obviously, the temperature and humidity conditions must be such to not only facilitate the dry down process, but to accelerate it. Each day the crop stands in the growth chamber beyond physiological maturity is a day which could have been used to grow the next crop.

The translocation rate of carbohydrates to the seed, the physiological maturation of abscission layers, and the process of drying in the spikes is not a well documented aspect of wheat growth. Data are required to develop adequate mathematical expressions of the relationships, in order to simulate the process and determine optimum harvest strategies.

### Current Practices

The time required to harvest 11.4 m<sup>2</sup> of wheat grown in the plant growth chambers at Johnson Space Center, place the above ground and root portions in bags, weigh the bags, and clean the trays was observed to be approximately 1.5 hours for 20

people. That's approximately 2.6 person-hours per  $m^2$  of effort to harvest and initiate biomass recovery and processing of a crop which took 80 days to grow. That averages about 2 minutes per day. But with startup and cleanup, a crew member is likely to spend much longer if harvest occurs each day. A much better scenario would be to harvest more than one day's supply at a time. The exact amount will be a tradeoff between the demand for space in the growth chamber, labor requirements for harvesting, and the costs of storage of the processed grain.

The numerical values of such statistics have little long-term merit because no accurate measurement was made of the time and motion of each worker, or was each worker supervised to be sure they were constantly performing their task. The processes which are best suited for mechanization or automation may be considerably different, and require much different times. Comparisons should be made only after mechanization and automation are integrated into the processes.

At Kennedy Space Center, McDonnell-Douglas personnel undertook the task of developing the sensor and robot control programs for a robot to reach into a canopy of mature wheat and remove each head from the stalk. Such an approach would minimize the amount of biomass which must be threshed, but it proved to be a most difficult and time-consuming task.

Commercially, farmers harvest grain crops with combines (machines that combine the processes of gathering, threshing and separating) with field capacities of 5 or more acres per hour. At this rate, the 11.4  $m^2$  chamber area would be harvested in 2 seconds! The crop is cut with a sickle-bar and guided by a finger or bat type reel onto a cross-auger which carries it across the grain platform to the feeder-conveyor which takes the crop to the threshing and separation mechanisms. The grain platform headers are often 20 feet or more in width. By adjusting the height of the platform, the operator can cut the crop just below the heads, thereby reducing the volume of biomass which must be threshed, which reduces the energy requirements for threshing and the amount of trash in the grain.

Japanese rice combines gather each row of stalks and by maintaining the plant orientation are able to insert just the heads for threshing. This procedure minimizes the energy required for threshing, it keeps the rice straw intact, whole and useful for mats, thatch, etc., and it permits rice to be harvested when the straw is relatively wet and green.

These large, American style machines have been designed for 1 G conditions and operate in only a very narrow range of crop properties, particularly moisture content. The scale of these machines is certainly inappropriate, and probably the materials handling mechanisms (cutter-bars, augers, conveyors, etc.) are as well. The Japanese rice harvesters maintain a positive control of the plants after cutting, which may make this technology adaptable for lunar or Martian gravity.

### *Proposed Automation*

Gathering the wheat crop would be greatly facilitated by growing the plants in pots which can be quickly removed from the growth chamber to initiate the dry-down process. The pots and soil/wick mixture can be immediately processed and recycled for the next crop. The wheat crop (roots and all) can be held in ventilated racks where waste heat and low humidities are used to dry the grain to the desired level. The robot arm would perform the task of moving the pots into carriers and transporting the carrier to the pot

and soil recovery area, and after the plants are extracted, moving them to the dry-down area. Because of the versatility of the robot, its grippers, and its sensors, very little if any new hardware will be required for gathering. The programs will be different from planting.

### **Threshing and Separation**

Once the crop has been gathered from the field and dried to the best moisture content for threshing, the grain kernels must be detached from the head and separated from the chaff or other plant parts. Detaching requires mechanical, rubbing motion with a minimum of impact which could cause damage to the grain. Centuries-old practices for separation (winnowing) utilizing differences in particle densities and their aerodynamic drag coefficients are also followed by modern machinery.

A model of the soybean material flow through a combine was developed by Miles and Tsai, 1987. Materials were divided into categories: heads or pods (with kernels attached), free grain (kernels detached or free), and MOG (material other than grain). The equations describing the rate of material flow through the combine and from one category to another were based on bio-physical properties of the crop and the machine design parameters such as conveyor speed, and cross-sectional area. Reed Turner developed the HarvesTrainer<sup>®</sup> personal computer program which models the harvesting, threshing, and separation of corn, wheat and barley for several models of John Deere combines. Mathematical models show the complex interaction between doing an adequate but not excessive job of threshing, and the size of sieve opening and counter-flow air volume (Mailander and Krutz, 1984; Mahoney and Srivastava, 1986; Kim and Gregory, 1989; Bjork, 1991; Nath, et al., 1982; Trollope, 1982). Excess threshing not only detaches the seed, it grinds the heads and stems into fine particles that are difficult to separate from the grain. Sieve openings may be adjusted to screen out the larger chaff particles. The fan speed must be adjusted to provide a sufficient counter-flow of air through the louvers to exceed the terminal velocity of the chaff, but not the grain. Problems occur when the thresher breaks the head and stems into a particle size distribution whose aerodynamic drag coefficients and densities overlap those of the grain. By properly adjusting the machinery, and by threshing when the proper crop bio-properties exist, clean, damage-free grain can be obtained.

### *Current Practices*

Researchers typically use a plot-thresher which detaches and separates the grain. In such a device, wheat plants are fed by hand in small quantities. A rotating drum with spikes rubs the head against a stationary set of spikes, and the detached kernels fall down into a catch pan. A small fan provides a cross-flow of air that blows the chaff into a bag.

Modern combines not only gather the crop, but also thresh and separate the grain as well. Sensors detect grain loss and measure the bio-properties of the crop, and microcomputers adjust the machine to optimize performance. Properly adjusted, modern combines harvest 95% or better of small grain crops. Over 80% of the losses occur at the header during the gathering process.

Conventional combines use rotating cylinders with rasp-bars, which rub the grain against open grates called concaves. Occasionally, in tough conditions, special rasp-bars

and concaves with intermeshed spikes are used. The clearance between the rasp-bars and concaves is adjustable for different crops and quantity of biomass. The openings in the concaves can be changed by adding or withdrawing curved wires or rods. The flow of material is radial, or tangential to the axis of rotation. As the heads are threshed, the kernels and chaff fall through the grates in the concaves to the cleaning mechanisms. Secondary separation occurs in the straw-walkers.

Axial flow combines use similar threshing mechanisms, except the flow of material is along the axis of the cylinder (termed a "rotor") which is mounted parallel to the axis of the combine. This mounting permits much longer and larger diameter cylinders (rotors) to be used. Since the threshing occurs over a much greater area, the process is usually more gentle than the conventional threshing mechanisms, and less grain damage occurs. Manufacturers claim that grain separation is enhanced by centrifugal force of the rotating cylinder.

Although the threshing and initial separation mechanisms of conventional and axial-flow or rotor machines are significantly different, the cleaning mechanisms still rely on the proven technologies of oscillating sieves with a counter-flow of air. Louvers in the sieves are adjusted to permit the grain to freely pass, but prevent larger biomass pieces to bounce across the top due to the oscillatory motion. Chaff particles the size of grain are prevented from falling through the sieves by counter-flow of air. The velocity of air through the sieve openings must exceed the terminal, or settling velocity of the chaff, but not that of the grain kernels. Air velocity is adjusted by modifying fan speed. Unfortunately, the actual velocity through the openings is affected by the density and uniformity of the mat of chaff on the sieves. The denser, heavier and thicker the mat, the greater the differential pressure, and the less the velocity. In case of non-uniformity, the thin areas may blow completely off, which permits most if not all of the air to flow through the hole. Excessive trash in the grain results from this situation.

### *Proposed Automation*

The size of modern combines is obviously much too large for a CELSS, but the efficiency and reliability of the proven mechanisms makes them very attractive for consideration. As the plot threshers have proven, the mechanisms for threshing and separation can be scaled to an appropriate size. No doubt, a robot could grasp each bundle of wheat and place the tips containing the heads into the thresher. However, it is not clear that the separation and cleaning mechanisms (sieves and fans) will work properly in less than 1 G conditions.

A suggested alternative is to accelerate the threshed grain and chaff mixture and utilize the difference in particle momentum to separate the kernels from the chaff. The mixture could be forced pneumatically out a tube onto a slightly cupped, spinning disk with short blades (similar to the spreader mechanism used on a bulk, dry fertilizer truck). Coming off the spinning disk, the kernels would have the greater momentum, since they would have the greater mass. An opposed flow of air would halt the horizontal movement of chaff quickly because of their larger aerodynamic drag coefficients. The grain kernels would move further away from the spinning disk because of their greater momentum and less drag. Additional enhancements, if necessary would be to create a velocity gradient in the opposed flow of air. This would permit particles to settle out of the horizontal stream

at distances proportional to their coefficients of aerodynamic drag. Additional separation is possible by adding a spiral separator, which permits the heavier and more round particles to roll faster, and be carried out by centrifugal force. Vibratory separation should also be considered.

The clean grain should be placed in a container which the robot can carry to a temporary queue, place it the dryer, and/or place in storage. While the chaff residues from the separation process can be returned to the crop biomass, the particle sizes are now much smaller, so a container must be used. This material can be fed into the machinery for the recovery process.

### **Recovery and Recycling of Inedible Biomass**

After the grain kernels have been detached, the stems and roots must be processed to recover the nutrients. Among the processes proposed are leaching, bio-digestion, and oxidation, all of which are more efficient if the plants are shredded or macerated. Leaching nutrients with acids and bio-digestion with enzymes, micro-organisms and/or animals may be better with the wet, green plant tissues. Oxidation would undoubtedly require not only fine particles, but dry materials as well.

In agriculture, devices used for changing the particle size of plant materials include forage choppers, hammer mills, and grinders. Forage choppers leave particles approximately 1 to 2 inches long, and work well with wet, green materials. Hammer mills and grinders work well with dry materials, and are capable of particle sizes of .1 inch or smaller. Hay conditioners which scuffs the outer layer of the stems and/or crimps the stems, are able to speed the drying process for the biomass.

The materials handling requirements to feed the plant residues to such machinery are rather simple. If the crop is still bunched, a robot could grasp the clump and force it into the machine. If not, the crop can be placed onto a conveyor which accelerates it to thin it out to the desired thickness and feeds it into the machine. The output of any of these machines must be delivered to the apparatus which effects the nutrient recovery. This could be by mechanical conveying, pneumatic conveying, or containers carried by robots.

### **Preprocessing**

The most likely preprocessing of wheat is drying the moisture content below what is best for harvesting (18%) to what is best for storage (14% or less). For storage less than a year 14% is considered acceptable for up to 2 years it is 13%, and for 5-years the wheat should be dried to 11-12%. Usually this is accomplished by heating air to reduce the relative humidity and blowing it through the grain (batch-dryer). Alternative methods include flowing grain across heated metal plates (continuous-flow dryer). Occasionally, for small batches of grain, microwave ovens are employed. Too rapid drying creates stress cracks in the seed whereas drying too slowly permits microorganisms to grow and damage the quality of the grain. If the drying time is too long, more moisture than necessary is removed, and in extreme cases, the seed become "cooked". The proper moisture content, drying rate, and drying time also depend on what the grain is used to make (Bruce, 1992). It is especially important to note that whenever any of the grain is



kept as seed for subsequent crops, that the damage during drying be kept low to maintain viability.

The basic principle is to keep the equilibrium relative humidity for the grain below 68%. Safe storage conditions can be determined from an equilibrium moisture content curve as given in ASAE Data D245.4 (ASAE, 1993) which are different for hard (Durum, high-protein, used for bread) and soft (pastry) varieties. Numerous models have been developed to predict the drying time and quality of grain, especially corn (Chung and Verma, 1991; Bunn and Wishert, 1991; Bruce, 1992; Giner, *et al.*, 1991; Parti, 1990; Sanderson, *et al.*, 1989; Sokhansanj and Bruce, 1987; Abawi, 1993).

The amount of grain harvested at one time from a CELSS plot is relatively small and can easily be placed in drying ovens by a robot. The ovens used to dry the biomass may also be used for drying the grain, provided the temperature is as prescribed by the ASAE procedures. The grain should be uniformly scattered across a pan with a screen for the bottom, and placed on a shelf in the oven. The oven should have air flowing through the screen vertically to remove the moisture. The sensors in commercially-available, hand-held grain moisture meters can be adapted to provide on-line, continuous measurement of moisture without opening the oven. Another sensing technique would be to monitor the air above the grain pan to detect a rapid decline in relative humidity, which would signal that the grain has reached the equilibrium moisture content.

Mechanization for this process requires that the container of grain from the threshing and separation process be poured uniformly on the drying pan, which is then placed on a shelf in the oven. After the grain is dried, the drying pan is removed from the oven, the grain is poured into a container which is sealed and placed in storage. The same robot used to manipulate materials in the growth chamber can also be used for these tasks, provided the base-rail extends into the processing chamber.

### Storage

The design considerations for storage include the volume required for the raw, edible products; and the environmental conditions (temperature, humidity, and oxygen concentration) necessary to sustain the quality for the intended shelf-life. The containers used to carry, dry and store the grain must be efficient in utilization of storage volume. The storage volume required depends on the crop yield, the harvest area, and the food reserve factor. For example, if 11.4 m<sup>2</sup> of wheat yielding 100 bu/A were harvested, then approximately 0.35 cubic feet of storage would be required. If a 3x reserve of wheat is desired, then  $3 \times 0.35 = 1.05 \text{ Ft}^3$  would be needed. Please note that two of the storage bins would normally be full, but the third would be somewhat less than full. Thus, the true amount of reserves is one less than the number of storage sites.

In storage, the grain moisture content will reach an equilibrium with the surrounding conditions, depending on temperature and humidity. Seeds very slowly respire, which converts stored carbohydrate and oxygen into carbon dioxide and water. Respiration proceeds with a  $Q_{10}$  of 2; that is, it doubles for each 10° C rise in seed temperature. Low temperatures also inhibit the growth of microorganisms such as molds and bacteria that lower the quality and in some cases make the grain unfit for human consumption. Thus the ideal conditions for grain storage are low temperatures (even below the freezing point of water), and low levels of atmospheric moisture and oxygen.

The automation required for storage includes automatic insertion and retrieval of containers of food. This could be on shelves, 1 unit deep, on which the robot could place items. A more sophisticated approach would be to develop a miniature warehouse storage and retrieval system with inventory control. Arguments for the robotic approach are similar to those used for the robotic handling of plants in the growth chamber. With machine vision, the robot could "see" each vacant slot and insert the food container into the next available space.

### **Food Processing**

Just as an army travels on its stomach, the amount of work accomplished by an astronaut crew will depend on having a wide variety, and ample quantities of tasty, nutritious foods. When selecting crop species and food processing techniques to provide dietary needs, taste preferences and nutritional demands for humans working in space environments must be considered. It is probable that the loss of calcium and muscle during micro gravity conditions will require diets considerably different from earth-base recommendations. After arriving on orbit, astronauts seem to choose spicier foods to consume. To ensure needs are met, astronauts must be included in decisions about crops and processing.

The automated food processing devices must retrieve the raw food products from storage, measure and pour the desired amount into the hopper for the food processor, whether it be a milling machine, pasta machine, or toaster. Bread, pastas, and cereals require different processing: grinding, milling, cracking, toasting, and extrusion. The machinery for these processes are different, so to provide a variety of foods from wheat or other grains, several machines will be required. However, the concept of a grain container that can be poured into a hopper by the robot, permits the materials handling to be automated without a lot of complication. The difficult task is to clean the machinery after use. This will require special end-effectors on the robot which can disassemble the key components of the machinery and place them in a washer. Later the robot can retrieve the components and reassemble them.

### **Food Preparation**

After the grain has been processed, it must be prepared into the food to be eaten by the astronauts. Flour that has been ground must be sifted, mixed with water and other ingredients and baked into bread, biscuits and rolls. Like other aspects of a CELSS, questions arise: How much of this should be automated? What tasks are better left to the crew? Should bread be baked in small amounts each day, or in larger batches each week? The answers probably depend on which tasks the astronauts enjoy doing, and which become drudgery to perform. As the frequency of occurrence increases and the drudgery becomes higher, the greater the need for automation.

Again the processes can be automated by robotic handling of containers of the food products.

## CONCLUSIONS

The myriad of tasks required to grow plants, process edible portions into food, and recycle inedible biomass into nutrients required by subsequent crops, could require large amounts of astronaut labor unless automated (Schwartzkopf and Brown, 1991; Schwartzkopf, 1991; Schwartzkopf, 1993). Conceivably, the amount of labor required for performing all the materials handling for planting, tending, gathering, separation and threshing, processing, recycling wastes and cleaning equipment could exceed the life-support capacity of a CELSS. Thus it is essential that automation become an integral component of CELSS research. Because of their versatility, robots offer an overall less complex and less cumbersome solution to mechanizing the materials handling tasks than hard, fixed automation. Individual processes such as threshing, chopping and grinding are best accomplished by special purpose mechanisms. Researchers around the world are developing the sensors, end-effectors, manipulators and robot control programs necessary to automate materials handling tasks for typical, earth-based plant production. Some of the robotic transplanting, culturing, and harvesting efforts are applicable to a CELSS, but in most cases additional technologies must be engineered.

Techniques for growing crops in controlled environments are being developed by CELSS researchers. Data on oxygen and water recovery, carbon dioxide scrubbing, nutrient and energy input requirements, and food production are being gathered for a number of candidate crops. Techniques for germination and growth with hydroponics are being discovered. Failure to simultaneously develop mechanisms which not only work well with the bio-physiological processes but also automate the procedures and reduce the manual labor requirements is a serious oversight. Engineers charged with automating current, proven production and recycling practices will face enormous challenges unless cooperation begins with the biological scientists immediately. The bio-physical science research and the engineering for automation should proceed cooperatively. Working together, the scientists and engineers will be able to develop hybrid techniques which satisfy the biological requirements for life support and the operational constraints of space, launch weight and labor. This is the only way to insure the successful development of a CELSS.

Because the options for automation are so numerous, a general purpose solution suitable for all crops is difficult to conceive. A systems engineering study based on animated simulation of specific CELSS scenarios should be undertaken to evaluate and compare alternative designs. Which tasks should be automated by fixed engineering, and which ones should be automated by programming a robot to provide the necessary actions? Which tasks should be performed by the crew? How much time does it take for the robot to perform a task versus an astronaut performing it? How much power is required by the robot? How much space is occupied by the automated machinery? What does it weigh? If the volume and weight of a CELSS plus its automated machinery and processing area were used to store food, and if water and oxygen were recycled by physical-chemical means, how many people-days of life could be supported? The answers to such questions can only be obtained by following the systems study with a laboratory study to validate the proposed automation, and to collect statistics on human/machine interactive performance. In addition to answering a number of basic biological questions,

the proposed Human Rated Test Facility (HRTF) at JSC should be used to answer many questions concerning mechanization and labor requirements for a CELSS.

A basic concept for automating materials handling required to grow wheat in a CELSS is proposed to consist of removable benches on shelves, filled with containerized plants (pots), which are transported by a robot to and from the processing area. The robot rides on a rail mounted overhead, and has numerous end-effectors (grippers) which enable it to perform many different tasks at any location in the growth and processing chambers. Liquid nutrients are recirculated to the benches by ebb and flow techniques used in the commercial plant production industry. Pots enable the robot to space plants dynamically as they grow to utilize the maximum amount of light possible, to cull plants not performing to minimum expectations, and to replace the culled plant with a vigorously-growing new pot.

In summary, the conclusions are:

1. Materials handling in a CELSS must be automated,
2. Robots are superior to fixed-automation,
3. CELSS tasks require unique sensors, end-effectors and manipulators for robots,
4. The bio-physical science research and the engineering for automation should proceed cooperatively,
5. An animated simulation approach is necessary to evaluate the myriad of alternatives for automation.

Immediate funding of scientific and engineering efforts to automate materials handling will produce short-term benefits and help ensure the long-term success of Controlled, Ecological Life Support Systems when needed for exploration of the Moon, Mars, or the rest of our Universe.

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