Development of the ALSARM-EE for a Biomass Production Chamber at the Kennedy Space Center

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Abstract

The objective of this research is development of an Advanced Life Support Automated Robotic Manipulator –End Effector (ALSARM-EE); a robotic system to be used in the Biomass production chamber (BPC) at Kennedy space center (KSC). The ALSARM-EE is composed of a seven degree-of-freedom robot system that has an automated control. It provides automated and manual data measurement capabilities while maintaining the chamber integrity by positioning a sensor array via remote operator commands. This paper shows robotic system requirements and presents the rationale behind the ALSARM and its end-effector. The attributes of this ALSARM-EE system are: (1) LabWindows software that can automate input measurement points or can load input points through “teach pendent”, (2) provide “master-slave” three-degree-of-freedom direction of the end-effector, and (3) integrated control framework providing closed-loop nonlinear learning control embedded in a model-based self-configuring autonomous system.

Key words

Biomass Production Chamber (BPC), Robotic Manipulator, End-effector, Autonomous Control System, Model Based Self-Configuration.

I. Introduction

The BPC research at NASA's KSC is performed on a regenerative life support system using hydroponics plant growth in a closed environment. It has been operating on an entire life cycle basis, and can be used to enhance our understanding of the required life support manipulations in a closed test bed. This, in turn, will provide a baseline for space applications (i.e. International space station and lunar based labs) [1][2]. The BPC is a sealed environment used for plant growth and oxygen regeneration (figure 1). The BPC is sealed so that water vapor and air can be recycled. The scientists in this program want to eliminate the personnel entry, therefore reducing the leak rate of air and the water vapor, and thus obtaining consistent measurements inside the chamber [3]. Total Biomass yields of the different crops (wheat, soybean, lettuce, and potato) were strongly dependent on environmental factors, such as the total lighting provided to the plants. Enabling technologies to keep man in space for long periods of time without re-supply are yet to be demonstrated. The practical means of achieving long-term presence in space is to cultivate biomass and utilizing recycling technologies that biomass production facilitates. The diverse technologies required for the biomass production in space for the provision of food and advanced life support operations have not yet been adequately integrated and demonstrated. It is feasible to develop a biomass-production model since plants generally grow in a predictable way under specific conditions. If a crop is given the same conditions, plant growth will proceed in the same way and the harvest will be within that specified by bio-production model to the order of magnitude of one percent. Consequently, under these conditions, a model of a plant growth can be developed easily. This new innovation, using a reliable robotic manipulator and the end effector equipped with various sensors will advance an automated biomass production system for space. The unique feature of this approach is the use of robotic systems to replace human labor, so that the BPC can maximize the ability to grow plants and minimize human interaction [4].

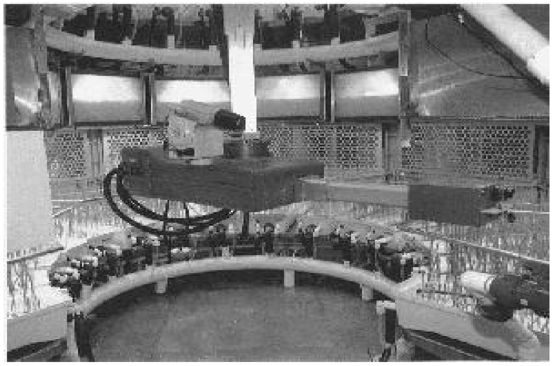

Fig 1. Biomass Production Chamber

II. Design of Robotic System

The ALSARM-EE design concept involves the use of off the shelf components integrated together to accomplish the movement and control of the various robot links. The robot’s primary function is to move within specified locations around the chamber receiving plant samples and measuring air temperature, relative humidity, air velocity and photosynthetically active radiation [5]. An IBM Pentium PC is responsible for user interfaces, robot control, and data recording for the ALSARM-EE. CVI's LabWindows software is the controlling software which uses C programming to tie graphical interface tools on the PC monitor to the robot's controlling I/O devices. An additional hand held interface, called a teach pendant, is used to control the robot positions manually from remote locations. Additionally, the ALSARM is controlled from an observation room approximately 100 feet away. The final concept is represented in figure 2 [5][6].

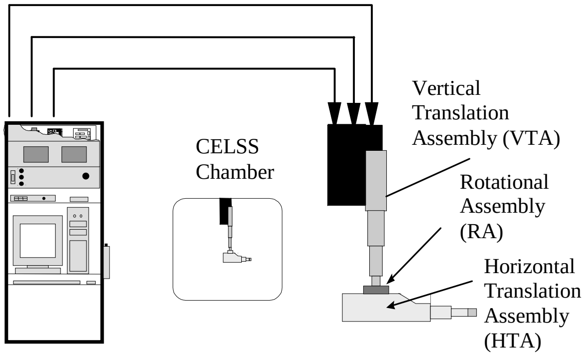

Fig 2. ALSARM design and control

Operational requirements:

Operational requirements consider a range of factors affecting the ALSARM. Factors such as physical compatibility of end-effector with supporting structure; identifying acceptable levels of reliability and fault tolerance; and method of control must be considered, along with the risk of system damage associated with operational procedure.

A. Environmental:

The effects of the surrounding environment on the end-effector system (and vice versa) are very critical. Suitable protection has been designed and integrated into the BPC. The material for fabrication of the end-effector shall conform to the specified environmental contamination conditions. Most importantly, being able to conform to the high humidity of the BPC

B. Controls requirement:

The end-effector shall be capable of teleported control via CVI's LabWindows and able to be controlled by a "joy stick" or "teach pendent".

II. 1 ALSARM

The ALSARM's modular design consists of two telescopic arms and a rotational joint. The robot is attached to the BPC through a recessed hatchway located in the center of BPC's ceiling. Deployment of the robot is accomplished by vertical, horizontal and rotational actuation. The vertical arm allows the robot to be positioned at any point in the vertical working plane. A rotational actuator that interfaces the horizontal arm with vertical arm is used for angular positioning.

ALSARM requirements:

- The robot shall cover a predetermined 3-D grid consisting of 864 points inside the BPC within 2 hrs.
- The movement of robot system between stowed and operational positions shall be automated.
- LabWindows software shall acquire and process data at 864 specified points with a 3-D grid over 2 hrs.
- Sensory hardware shall measure desired quantities.

ALSARM design:

The ALSARM is a modular design consisting of three groups; Vertical Telescopic Arm (VTA), Rotational Actuator (RA), and Horizontal Telescopic Arm (HTA). These three groups are illustrated in figure 3.

VTA: Vertical Telescoping Arm will be accomplished through the use of a Serapid Rigid Chain and a Telemag telescopic pillar boom. These particular systems were chosen for their strength, accuracy, and durability. These components, coupled with a rugged mounting brace, will provide the robot arm with the necessary support and stability. The Telemag boom, a sturdy square aluminum pillar, consists of an outer casing and five inner casings. The inner casings are pushed out of the outer casing in a straight line by the force provided by the Serapid Rigid Chain. The frictional force that keeps the casings together is a result produced by a tight fit of the casings against a delrin surface. Delrin has a static friction coefficient of 0.2. The extension of each casing will cease at pin stops, which give an active length of 488 mm (19.2 in) and an overlap of 112 mm (4.41 in). All inner casings are fully collapsible into the outer casing and are each 600 mm (23.6 in) in length. The maximum stroke length of the Telemag boom is 2438 mm (95.8 in).

RA: An important requirement of ALSARM is the ability to rotate to any desired position in the BPC. The rotational sub-assembly is designed to meet this requirement. A pancake motor and a harmonic drive were used to create the necessary gear reductions. The harmonic drive and pancake motor were integrated into an actuator housing, located between the HTA and the VTA. The pancake servomotor is mounted under the housing allowing space for the static link of the HTA. Materials were selected for their strength in design as well as to minimize lubrication in the gear set. A stress analysis was conducted to determine the size and number of bolts on the mounting plates. Since safety is of extreme importance, an FMEA was conducted to determine hazards in the rotation system.

HTA: The horizontal telescoping arm component of ALSARM provides an extension for positioning of the end-effector. The VTA and rotational actuator assemblies provide the horizontal plane of action and azimuthal coordinates. The HTA must be capable of extending the end-effector 1574.80 mm (62.00 in) from the center of the CELSS chamber. It accomplishes this by the use of three telescopic Telemag pillars. The overall stroke length of the three pillars is 1244.60 mm (49.00 in) and the links are fully retractable. In addition to housing the telescopic pillars, the base link contains a Serapid Chain and servomotor for actuation and pulleys for cable handling.

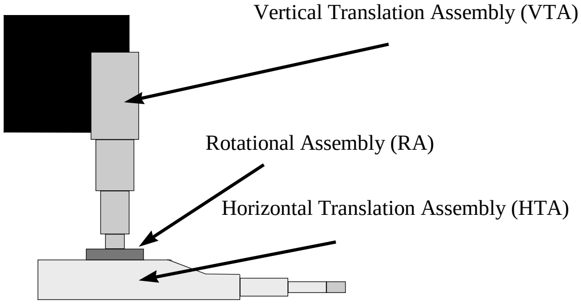

Fig 3. ALSARM

II. 2 End-Effector

The End Effector is an extension of the robot manipulator's horizontal-telescoping arm. The End-Effector is capable of retrieving samples and data from the BPC specimens.

End-Effecter design requirements:
Primary application is to retrieve vegetable samples; its requirements were,

- Angular, Limit: ±30º in Pitch and Yaw
- Rotational Limit: ±180º from Center
- Gripping Space Capacity: Stem of Vegetation
- Gripping Weight Capacity: Less than 1 Pound
- Cutting Capacity: Stem of Vegetation
- Boundary: About 9 inches in Length (from End of Robot Manipulator to End of Gripper)
- Low Contour Design
- Contamination-Free Environment

Complementary requirements are,

  - Robustness
  - Ease of Cutting Device Replacement
  - Ease of Interfacing with Existing NASA Databases
  - Reliability of Apparatus

Functional Decomposition:
The functional decomposition systematically reduces the necessary task of the end-effector into basic immutable physical components that allow their arrangement into a more deliberate logical arrangement.

Mechanical Functions:
The mechanical functions include positioning the end-effector in front of the sample, gripping the stem of the sample, and cutting the stem of the sample.

1) Position the gripper: a) Motion is initiated that provides a platform for all other functions, b) Impetus is provided that allows mechanical motion, c) The allowed motion follows a specific motion profile.
2) Grip the object: When motion ends, the End Effector is placed in close proximity to the object. The object must then be grasped for cutting.
3) Cut off the object: Once the object is grasped, the stem is cut for removal of object.

Control Functions:
The control functions include commanding the mechanical functions using a computer program and bringing the sample to the release chamber.

1) Direction Determination: The provided control will determine the correct direction given operator input or limit breaching event.
2) Limit determination: The control will determine if a hardware or software limit has been violated.
3) Emergency stop condition generation: The control will provide a method for generating an emergency stop command from operator input.

Power Functions:
The power functions covers all hardwired components in addition to power supplies, connectors, and computers.

Manipulation

A. Dexterity:

A parallel gripper end-effector provides the minimum level of function necessary to securely clamp a limited range of objects like plant stems and separate them by using sharp blades as illustrated in figure 4.

With some modification in the gripper assembly, it can be easily made to cut and hold the plant samples.

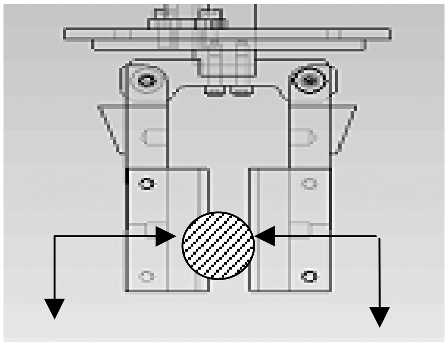

Fig4. Gripper grasping and cutting

B. Compliance:

Compliance is a most important attribute for the end-effector grasping system and it provides several benefits,

- As it is equipped with spring-loaded grippers, it ensures a smooth interaction force as gripping elements make contact with the object.
- The grippers hold the object firmly and the blades then cut it smoothly and the sample can be transferred securely from one place to other.

C. End-Effector (EE) System:

The EE 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. There are two design structures for the placement of the motors; either the motors are placed near the joints or the motors are set back to translate the forces to the joints. Both designs have pros and cons, which were weighted carefully. By placing the motors at the joints, stronger torques could be achieved with fewer parts. However, this also creates more weight further from the support, requiring stronger joints. In addition, the sensor wires must run over the joints freely. With the motors positioned near the back, the weight is taken off the joints, requiring less torque, and the wires only need to pass through one joint. However, to translate the forces to the joints, additional parts are required that must be capable of translating the torque to the end part. Since the first concept causes the gears to grind down to failure due to too much load to EE, it was designed to alleviate the problem by moving the motors back and constraining them by two plates called the motor mounts. In addition, gear boxes where attached to the joints to allow stronger loads. The assembly of the End-Effector is shown in figure 5.

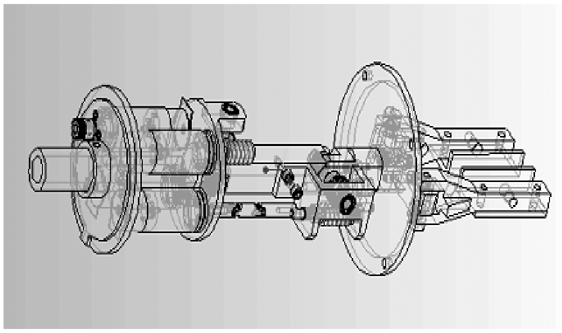

Fig 5. End-Effector

III. Autonomous Control System

An integrated control framework was developed that provided autonomy, monitoring, diagnosis, fault-recovery and self-learning execution, for both dynamic and steady state controls. It also provided stable operation of the robotic system, making sure the growth and health of the plants under production are preserved. Specifically, the proposed new control scheme addresses the following technical difficulties currently encountered in the designs of an autonomous management system: 1) processes and components in the system must be controlled continuously, and their growth and health have to be monitored in the presence of dynamic variations 2) design of an autonomous system operating in an unknown and changing environment. In order to overcome the two major obstacles, the proposed intelligent control framework will achieve the following technical objectives: 1) Robustness in a changing uncertain environment, 2) Fault tolerance, 3) Autonomous and self-reconfiguration, and 4) Intelligence.

The block diagram of the proposed control system is illustrated in figure 6. The system consists of a set of actuators that drive the robotic system of the BPC. Sensors will monitor system variables (or the states) and the measured signals will pass through optimal filters.

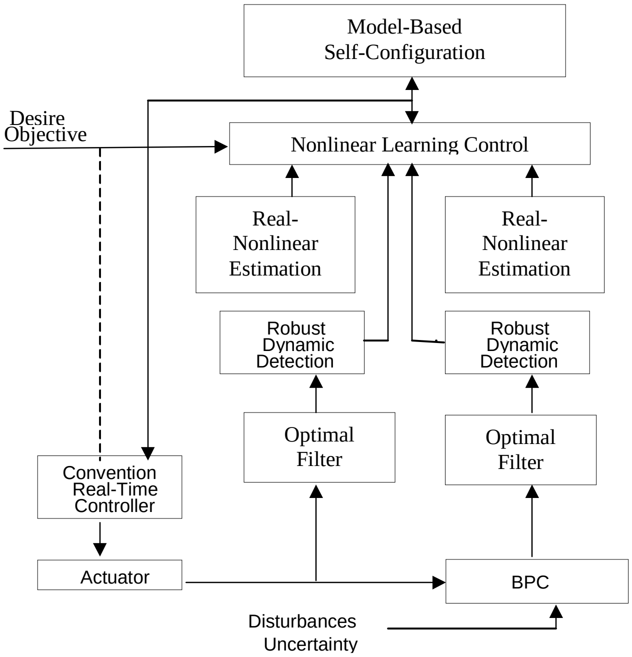

Fig 6. Control System Block Diagram

The filtered signals will then be sent to the conventional control block for real-time execution after passing through the fault detection module and robust control module. In the fault detection module, health of sensors is monitored using robust measures so that fault identification can be accomplished in the presence of significant uncertainties. Meantime, the same module also monitors growth of plants. When growth of plants is other than desired, the diagnostic algorithm will invoke the nonlinear learning control law, which is capable of guaranteeing performance. When a fault is detected, nonlinear estimation block is activated so that control action can be synthesized after excluding the faulty sensor. Selected signals from these blocks will be fed to the expert module based on heuristic knowledge in which global information can be assessed to handle the evolving environment, to make decisions, and to define control objectives. In summary, the proposed intelligent control framework has a hierarchical structure and consists of the following layers/components:

- Local control at the process/component level (bottom and local level).
- Discrete monitoring and fault-recovery control (intermediate and local level).
- Individual estimation and monitoring device (intermediate and local level).

- Nonlinear learning control (intermediate and regional level) [7,8].
- Model-based reasoning for intelligent control, *Livingston* (top and global level)[9].

Model-Based Self-Configuring (top level)

NASA has developed a model-based reactive self-configuring autonomous system called Livingston [9]. Livingston is a model-based discrete controller that infers the current mode of all system elements being controlled and determines actions that can reconfigure the system to achieve the currently desired configuration goals. The role of the model-based self-configuring is to oversee and confirm the application of a controller correction. In order to manage an autonomous reconfiguration of the BPC, it requires defining the concepts of operating and failure modes, repairable failures, and configuration changes. Then, configuration managers make extensive use of a model to infer the BPC's current state and to select optimal control actions to meet configuration goals. As shown in figure 7, a *model-based* configuration manager uses the BPC transition model to determine the desired control sequence in two stages – mode identification and mode reconfiguration and control. Mode identification incrementally produces all BPC transitions from the previous configuration such that the models of the resulting configurations are consistent with the current observations. Mode reconfiguration and control determines the commands to be sent to the BPC such that the resulting transitions drive the BPC into a configuration that achieves the configuration goal in the next state.

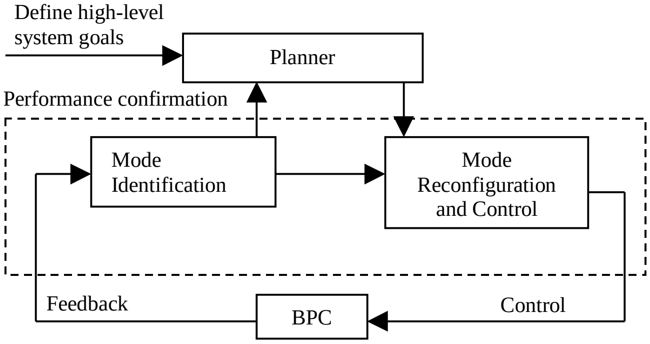

Fig 7. Model-based self-configuring management

Nonlinear Learning Control (intermediate level)

A learning control is one that not only stabilizes the system and guarantees performance for all uncertainties within their bounds but also enhances the transient performance from operation to operation by taking advantage of the periodicity of the repeated system tasks. The proposed learning control is based on a hybrid, continuous and discrete, Lyapunov argument so that global asymptotic stability can be achieved with respect to the number of operations.

Since the control objective is to obtain asymptotic link tracking, we define the tracking errors to be,

$$e = \theta^d - \theta \qquad \dot{e} = \dot{\theta}^d - \dot{\theta}, \qquad \text{and} \qquad x = \dot{e} + \lambda e \qquad (1)$$

where, $\theta \in \Re^n$ is a vector of joint angle variables, θ^d denotes the desired trajectory that the robot should track, and x is a [n x 1] filtered link tracking error with a positive design constant λ. Then, the tracking error of ALSARM-EE can be written in terms of the filtered tracking error (1) as the state-space form. Note that for simplicity the EE dynamics are included in the manipulator dynamics. It follows that

$$\dot{x}_j = \ddot{\theta}^d + \lambda \dot{e}_j - M^{-1}(\theta_j) N(\theta_j, \dot{\theta}_j) - M^{-1}(\theta_j)\tau \qquad (2)$$

where, $M(\theta)$ is an [3 x 3] inertia matrix and j denotes the index of learning trial and

$$N(\theta, \dot{\theta}) = V_m(\theta, \dot{\theta})\dot{\theta} + G(\theta) + F(\dot{\theta}) + T_L$$

where, $V_m(\theta, \dot{\theta})$, $G(\theta)$, and $F(\dot{\theta})$ are [3 x 1] vectors representing the centripetal and Coriolis terms, gravity terms, and static and dynamic friction terms, respectively. T_L is a [3 x 1] vectors representing an additive bounded torque disturbance and $\tau \in \Re^3$ is a vector of input torque. Then, the error system model can be classified functionally by its dynamics characteristics as that,

$$\dot{x}_j \overset{\Delta}{=} M^{-1}(\theta_j) f_j(\theta_j, \dot{\theta}_j, t)\psi(t) + g_j(\theta_j, \dot{\theta}_j, e_j, x_j, t)$$
$$- M^{-1}(\theta_j)\,\tau_j$$

where, $\psi(t) \in \Re^3$ represents a vector of unknown periodic time functions that are invariant from trial to trial in order to be learned by learning control part, and $f(\cdot) \in \Re^{3x1}$ denotes a known nonlinear matrix function. The vector $g(\cdot) \in \Re^3$ represents nonlinear uncertainties but bounded by known, well-defined positive functions that are locally uniformly bounded with respect to $e_{j,} x_j$, and uniformly bounded with respect to *t*.

Based on the important properties of the robot dynamics [10], the proposed learning control has the formulation

$$\tau_j = F(\theta_j, \dot{\theta}_j, e_j, x_j) + L(\theta_j, \dot{\theta}_j, e_j, x_j, \Delta_j)$$

where, $F_j(\cdot)$ is the feedforward, robust, control part. $L_j(\cdot)$ is the learning control part and Δ_j is the learning contribution from trial to trial. The proposed design of learning control is based on Lyapunov's direct method and the objective of controlling of the system is to make $x_j \rightarrow 0$ as $j \rightarrow \infty$ The control τ_j is designed such that it would provide global asymptotic stability of the link-tracking error in which learning control part $L_j(\cdot)$ and feedforward control part $F_j(\cdot)$. Since non-parameterizable dynamics along the desired trajectory are compensated by learning control as well as parameterizable dynamics such as $M(\theta_j)$, $V_m(\theta_j, \dot{\theta}_j)$, and $G(\theta_j)$, it follows without loss of any generality that,

$$M(\theta_j)\ddot{\theta}^d + V_m(\theta_j, \dot{\theta}_j)\dot{\theta}_j + G(\theta_j) + F(\dot{\theta}^d) + T_L(\theta^d)$$
$$\overset{\Delta}{=} f_j\, \psi(t) \qquad (3)$$

Rest terms of (2) after taking (3) belong to $g(\cdot)$, and we derive the bounding functions for $g_j(\cdot)$ in order to design the feedforward control part.

$$g_j = M^{-1}(\theta_j)[T_L(\theta_j) - T_L(\theta^d) + F(\dot{\theta}_j) - F(\dot{\theta}^d)] \\ + \lambda \dot{e}_j$$

Since, $\left\| T_L(\theta_j) - T_L(\theta^d) \right\|$ and $\left\| F(\dot{\theta}_j) - F(\dot{\theta}^d) \right\|$ are bounded by known functions e and $\dot{e}$, respectively, it follows that,

$$\left\| g_j \right\| \le \rho_e(\cdot) \left\| e_j \right\| + \rho_x(\cdot) \left\| x_j \right\|$$

where, $\rho_e(\cdot)$ and $\rho_x(\cdot)$ are some known positive definite functions. Then torque control input τ_j and the learning law are designed as,

$$\tau_j = \left[\frac{\alpha}{2} f_i \cdot f_j^T x_j + x_j + \overline{m} \rho_x x_j + \rho_v \left\| \dot{\theta}_j \right\| x_j + e_j \right. \\ \left. + \frac{1}{4} \overline{m}^2 x_j \frac{\rho_e^2}{\lambda} \right] + f_j \Delta_j ,$$

$$\Delta_j = \Delta_{j-1} + \alpha f_{j-1}^T x_{j-1} ,$$

where, α is a design constant, $\overline{m}$ is known upper bound of $M(\theta)$, and ρ_v is known bounding function given by $\left\| V_m(\theta_j) - T_L(\theta^d) \right\| \le \rho_v(\theta_j) \left\| \dot{\theta}_j \right\|$.

Remarks

An innovation in this research is on the integration of the proposed robust control/estimation technique with the expert module. While the expert module is capable enough for analyzing potential faults and providing intelligent solutions to detected problems, its process models and suggested control actions are discrete. Through the introduction of uncertain model, learning control, robust estimation, and robust performance measures and through combining them with the reactive, model-based expert module package, the proposed control framework becomes truly autonomous, intelligent and robust. Therefore, the proposed intelligent control system will reduce the cost, enhance reliability, and increase safety, allowing the BPC to be operated in a significant dynamic environment.

IV. Conclusion

The design and production of the ALSARM and the End-Effector systems is a complex process and final embodiment is inevitably a compromise between many contradictory criteria. The innovative control framework provides autonomous operation of the robotic system in the BPC. The ALSARM, End-Effector and control system design provides synchronization, which is suitable for a compromise between the device's complexity and its manipulative ability. The ALSARM and End-Effector is a multi-tasking robot, which will measure temperature, relative humidity, air speed, and light intensity. A master-slave end-effector will retrieve vegetation samples from the BPC. Thus, satisfying the various system and environmental constraints. This mechanism eliminates human intervention in BPC, avoiding contaminations and leakage of foreign elements, which allow consistent experimental procedure inside the chamber. The ALSARM-EE 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).

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