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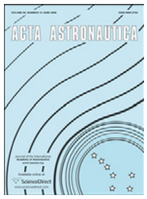

Controller development of photo bioreactor for closed-loop regulation of O_2 production based on ANN model reference control and computer simulation

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ABSTRACT

When Bioregenerative Life Support System (BLSS) is used for long-term deep space exploration in the future, it is possible to perform closed-loop control on growth of microalgae to effectively regulate O_2 production process in emergencies. However, designing controller of microalgae cultivating device (MCD) by means of traditional methods is very difficult or even impossible due to its highly nonlinearity and large operation scope. In our research, the Artificial Neural Network Model Reference Control (ANN-MRC) method was therefore utilized for model identification and controller design for O_2 production process of a specific MCD prototype—photo bioreactor (PBR), based on actual experiment and computer simulation. The results demonstrated that the ANN-MRC servo controller could robustly and self-adaptively control and regulate the light intensity of PBR to make O_2 concentrations in vent pipe be in line with step reference concentrations with prescribed dynamic response performance.

1. Introduction

When manned long-term deep space exploration is conducted in the future time, it is critically important to build Bioregenerative Life Support System (BLSS) imitating structure and function of natural ecosystem to revitalize food, O_2, drinkable water and other basic living necessities for astronauts and simultaneously recycle various wastes in bioregenerative manner. Compared with higher plants and animals, microalgae could have special advantages of high metabolism flexibility and growth rate as well as extensive adaptability and strong controllability, so they could be selected as a powerful tool for matter circulation and regeneration [1]. A great number of experiments focusing on microalgae cultivation have been currently carried out for safeguarding the balance of material exchange and the overall equilibrium of BLSS, and some new intensive, sustainable, and controllable cultivating technologies have been put forward as well. For example, the relationship between the growth rate of microalgae, *Chlorella vulgaris*, and the intracellular chlorophyll content under the different temperatures and light intensities was determined to select the best condition for microalgae cultivation and O_2 regeneration applicable to BIOS-1–3 [1]. The cyanobacteria, *Cyanothece sp. ATCC51142*, was used to regulate the gaseous composition, supply O_2, protein and fat for crew members in BLSS [2]. The blue algae, *Spirulina platensis*, was also cultivated for waste disposal as well as O_2 and probably edible biomass supply for astronauts [3].

Nevertheless, the BLSS and its subsystem like microalgae cultivating device (MCD) could be regarded as

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multivariable complex systems having sophisticated internal structures, numerous parameters as well as high nonlinearity and uncertain behavior characteristics, their proper nonlinear controller could not be designed precisely with analytical and synthetical methods, and they often have wide operation ranges without fixed operating points, so traditional approach like PID control based on linearization of the nonlinear systems would be infeasible. In addition, they necessarily encounter unanticipated internal variations and external disturbances during operation process and, hence, the open-loop control without feedback information, extensively used in current BLSS and its subsystems studies, is also unable to work well due to lack of stability [1,3].

In our research, Artificial Neural Network Model Reference Control (ANN-MRC) method was tentatively used to design an effective controller for feedback regulation of O_2 production in a photo bioreactor (PBR), a specific prototype of the MCD applied to efficiently cultivate microalgae, and swiftly regenerate O_2 and restore O_2 concentration to nominal level in BLSS under emergencies of gases concentration imbalances. The ANN-MRC servo controller was designed by digital simulation and validated, verificated and rapidly prototyped by real-time simulation [4]. The result showed that ANN-MRC servo controller could effectively control light intensity of the PBR to enable the target O_2 concentration in vent pipe of PBR to track and be in accordance with the reference concentration with good dynamic response performance.

2. Materials and methods

2.1. PBR prototype

The PBR used in our research was a 1.5 L plate-type bioreactor where blue-green algae, *S. platensis*, was cultivated in semicontinuous mode using synthetic human urine [5] and CO_2 as substrates introduced through an inflow pipe and an aeration pipe, respectively. A constant temperature of 30 °C and one atmosphere pressure were maintained throughout the experimental period. The *S. platensis* cultivation was illumined by light emitting diodes (LED) designed with red (680 nm) and blue (425 nm) lights, and the total intensity ranged between 50 μmol $m^{-2}\,s^{-1}$ and 300 μmol $m^{-2}\,s^{-1}$ regulated in pulse-width modulation (PWM) mode. The air flow rate of 100 L h^{-1} in aeration pipe was applied to both meet CO_2 requirement of microalgae and wash out the internal wall of vessel to prevent biofilm formation. The O_2 generated from *S. platensis* photosynthesis was transmitted from liquid phase to gas phase and finally expelled out of PBR through a vent pipe (Fig. 1). The 10 ml of buffer solution containing $NaHCO_3$ (13.6 g L^{-1}) and Na_2CO_3 (4.0 g L^{-1}) was periodically added in culture medium to adjust pH of liquid phase to 9 consistently during the operation. In order to keep *S. platensis* in the exponential phase all the time, its cell concentration should be kept at 5–7 g L^{-1} in term of our PBR, hence the suspension of 0.42 L must be periodically removed from the PBR via the overflow at the moment when the biomass was over 7 g L^{-1}, meanwhile, fresh buffer culture medium with equivalent volume was imported for the biomass concentration reverted back to 5 g L^{-1}. The light intensity, the essential factor of photosynthesis, was regarded as the only limiting factor of *S. platensis* growth [6], and other factors like temperature, CO_2 concentration, gas pressure, minerals and organic acids, etc. were kept normal and adequate throughout the experimental period [7,8].

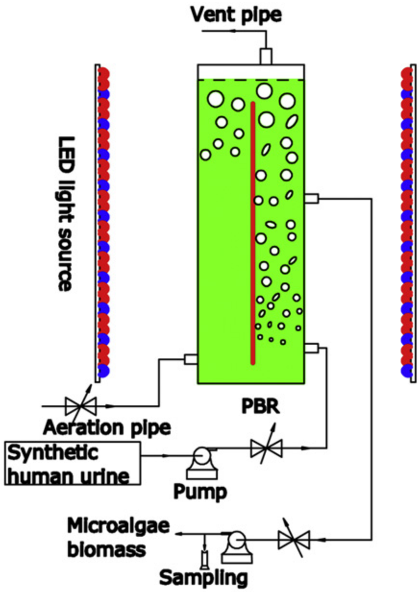

Fig. 1. Schematic diagram of PBR.

2.2. Design of ANN-MRC servo controller by digital simulation

Nowadays, ANN-MRC has been applied successfully in the identification and control of complicated systems, the universal approximation capabilities of the multilayer perceptron make it be widely applied in modeling nonlinear systems and general-purpose nonlinear controllers [4,9]. The ANN-MRC servo controller is composed of a reference model and two ANNs. One ANN (*ANN_id*) was firstly trained for PBR model identification based on experimental data, then a proper reference model was specified according to design requirements, and finally another ANN (*ANN_ctrl*) was trained as a highly self-adaptive and robust controller for feedback control and regulation of *ANN_id* input to make its output track and be in correspondence with the reference model output, which suggested that closed-loop PBR with ANN-MRC servo controller could have behavior similarity with the reference model.

2.2.1. ANN system identification

The input and output of PBR were light intensity and O_2 concentration (volume percentage) in the vent pipe, respectively. Input–output time-domain experimental data were obtained via simultaneously recording changes in light intensity acting on PBR and measuring O_2 concentration responses in the vent pipe from sensor. These long-term experimental data were divided into two parts: one part was used for *ANN_id* learning and training, and