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Adaptive critic design and Hopfield neural network based simulation of time delayed photosynthetic production and prey–predator model

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A B S T R A C T

This paper presents a neural networks simulation of two complex adaptive ecological systems with a discrete time delay. The first system is related to the photosynthetic production of phytoplankton, the second with a time delayed prey–predator system incorporating a prey refuge. The iterative adaptive critic design is developed to simulate the maximal photosynthetic production of the mechanistic model of phytoplankton photosynthesis with discrete time delays. The prey–predator system is simulated using back-propagation learning of infinite-dimensional dynamical systems. The proposed simulation method is based on the time-dependent recurrent learning of continuous-time Hopfield neural network with a discrete time delay with the prey–predator system as a teacher signal. Furthermore, numerical calculations are included to demonstrate the proposed simulation algorithms.

1. Introduction

The purpose of this paper, which connects to and provides more information about our previous work [26], is to use the neural networks methods in the study and simulation of the nonlinear complex adaptive ecological systems. Complex adaptive systems (CAS), systems that involve many components that adapt or learn as they interact, stand at the heart of important contemporary problems. The study of CAS poses unique challenges: Some of our most powerful mathematical tools, particularly the methods involving fixed points, attractors, and the like, are of limited help in understanding the development of CAS [19]. One type of new methods and tools to simulate CAS is based on artificial neural networks (ANN), which were developed initially to model biological functions and currently are widely use in all fields of science. A few applications of this method were reported in ecological and environmental sciences at the beginning of the 1990s. For instance, Colasanti [6] found similarities between ANN and ecosystems and recommended the utilization of this tool in ecological modelling. Relevant examples are found in very different fields in applied ecology, unsupervised and supervised neural networks to predict dissolved oxygen concentration, [1], modelling spatial dynamics of fish [11], neural network for identifying fishing set

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positions, [21], predicting phytoplankton production [36], etc. Most of these works showed that ANN performed better than more classical modelling methods.

In this paper we propose two possible applications of artificial neural networks with a higher degree of mathematical structure. We provide a detailed examination of the simulation process of phytoplankton photosynthesis using a mechanistic dynamical model, implementing the adaptive critic designs and feed forward neural networks. We hold that the photosynthetic production must be optimized in a simultaneous way both locally and globally. To implement these strategies, we use the methods from the optimal control theory of nonlinear systems with discrete time delays. Apart from the above, we also examine the simulation of the prey–predator model. For this simulation, the continuous Hopfield neural network with discrete time delays is implemented.

It is commonly known that the ability of artificial neural networks to approximate arbitrary nonlinear functions plays a key role in the use of such networks as components or subsystems in identifiers and controllers [40]. What is more, it was also used in the area of universal function approximation in order to solve the optimal control problems forward in time to approximate the costate variable. The analytical solutions are quite scarce [15] although a number of numerical computation approaches have been introduced, conf. [3,17,22,31,37]. The great majority of the studies on the numerical methods for the solution of general optimal control problems deals with the algorithms for solving the discretized problems. The basic idea behind these methods is to apply the nonlinear programming techniques on the resulting finite dimensional optimization problems [4,17]. Then neural networks are used as a universal function approximation to solve the finite dimensional optimization problems forward in time with adaptive critic designs [28,29,40] to approximate control and the costate variables.

In the previous work [24] we enlarged the adaptive critic design proposed in [29] to the optimal control problem with control and state variable constraints, which was generalized to the optimal control problem with a discrete time delay in [25]. Using the modified adaptive critic design based algorithm for the time delay systems presented in [25], we consider a simulation of the maximal phytoplankton photosynthesis production in the mechanistic model of phytoplankton photosynthetic production depending on the light intensity I with a discrete time delay, which was mathematically investigated in detail in [23]. The main result presented in [23] is the description of the adaptation process of phytoplankton after a shift from one light intensity I_1 to another I_2. The second simulation method is concerned with the back-propagation learning of infinite-dimensional dynamical systems using a continuous-time Hopfield neural network with a discrete time delay. We propose a new algorithm of time-dependent recurrent learning to simulate the chaotic dynamic of CAS, where the Lagrange multipliers, to compute the cost function gradients, have a significant importance [38]. The predator-prey model with a time delay [20] is used to provide a numerical experiment.

The structure of the paper is as follows. In Section 2, we present the description of the model of adaptive photosynthetic production with a discrete time delay. Section 3 contains a short description of the discrete time delay prey–predator system. In Section 4, we introduce the optimal control problems with delays in state and control variables subject to control and state constraints. We provide a summary of the necessary optimality conditions, present a short summary of the basic results, which also includes the iterative numerical methods. Section 5 contains a short description of the adaptive critic design based on neural networks for the optimal control problem with delays in state and control variables subject to control and state constraints. Further, we introduce a new algorithm to solve the optimal control problems. The new proposed methods are applied on the presented model to compare the short-term and long-term photosynthetic production. In Section 6, we provide an overview of back-propagation learning of infinite-dimensional dynamical systems and propose a new algorithm to calculate the gradient of the cost function. In Section 7, several simulations of two presented CAS are carried out. Section 8 is devoted for conclusion.

2. A mechanistic model of phytoplankton photosynthesis

The mathematical models of photosynthesis in bioreactors are important not only in basic science, but also in the bioprocess industry [10]. There exists a class of models derived from the concept of photosynthetic factories proposed by Eilers and Peeters [7]. The model and its dynamic behaviour was also discussed in [8,23,30]. Wu and Merchuk [43] introduced an approach to model the kinetics of the photosynthetic systems in the photobioreactor design using an alternating light/dark mode. Supposing that phytoplankton adjusts the rate of its photosynthetic production with the aim to maximize production, we examine two such strategies, i.e. instantaneous production and integral maximum production. The mechanistic model of phytoplankton photosynthesis stands at the core of the following consideration. It is based on the unit processes in the cellular reaction centres termed *photosyntheticfactories*(*PSF*). Algal physiology [7] suggested that the PSF can appear in three states: x_1 – resting, x_2 – activated and x_3 – inhibited. The photons are captured by a PSF in state x_1 which transforms to state x_2. The PSF in state x_2 can either return to state x_1 at a constant rate γ and with a discrete time delay τ_p or pass to the inhibited state x_3 (see Fig. 1). The transitions between states depend both on light intensity and time. The probabilities of the PSF being in the state x_1, x_2 or x_3, are given as p_1, p_2 and p_3, respectively. Transitions between states can be expressed as follows:

$$\begin{aligned}
\dot{p}_1(t) &= -\alpha I p_1(t) + \gamma p_2(t-\tau_p) + \delta p_3(t) \\
\dot{p}_2(t) &= \alpha I p_1(t) - (\beta I + \gamma) p_2(t) \\
\dot{p}_3(t) &= \beta I p_2(t) - \delta p_3(t).
\end{aligned} \tag{1}$$