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A novel model predictive control scheme based on bees algorithm in a class of nonlinear systems: Application to a three tank system

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ABSTRACT

This paper proposes a novel algorithm for utilizing bees algorithm in a model predictive control (MPC) in order to control a class of nonlinear systems. The bees algorithm is utilized in order to solve the open loop optimization problem (OOP), and it is based on the foraging behavior of honey bees. The proposed algorithm makes use of the bees algorithm for minimizing a predefined cost function in order to find the best input signals subject to constraints and a model of the system. The class of systems considered in this paper includes autonomous nonlinear systems without delay and with continuous and discrete inputs. The proposed algorithm is validated by simulating a three tank system as a case study. A comparison between the proposed novel MPC with different predictive horizons and a conventional MPC demonstrates the potential advantages of the proposed method such as reduction in computation time, good convergence toward desired values and ability of control management. Simulations also show the simplicity of applying and efficiency of the proposed algorithm for designing an MPC based on the bees algorithm.

1. Introduction

Nowadays model predictive control (MPC) is one of the mature and commonplace control approaches in which an explicit and relatively accurate model of a system is directly used to predict the future response of the system [1]. Such popularity is mostly due to its high performance, constraint imposing capability and simplicity. An MPC is applicable in many practical and academic systems and its results strictly depend on the model of the system [2–7]. There are different approaches for designing an MPC such as model algorithmic control, dynamic matrix control and internal model control [1]. In the mechanism of an MPC, between each two consecutive sampling time an algorithm is utilized to compute the best adjustments of the variables in order to optimize the results of a system based on a predefined cost function and regarding to the model of the system [8]. There are several publications giving good insight about the MPC and its applications [1,8–10].

In spite of the fact that the MPC is ubiquitous and widely has been used in many industrial applications, still many researches are done in this field. In these researches, scholars try to extend the scope of the applicability of the MPC, to increase the optimality of the MPC and to decrease the computational efforts of the MPC [2–7,11–16].

Ławrynczuk [2] introduced an algorithm based on an on-line neural model of the process to increase accuracy and computational efficiency of suboptimal MPC. He showed the suboptimal algorithm requires solving only a quadratic optimization problem. Through simulations it was proved that the proposed algorithm noticeably decreases the computational effort. In 2012 [5], Huang, Li and Xi studied the problem of the mixed $H2/H\infty$ robust model predictive control (RMPC) for a class of discrete-time systems in presence of structured uncertainty and disturbances. They proposed a multistep control strategy to improve the performance and enlarge the feasible region of RMPC. They also introduced an advanced version of their proposed RMPC to decrease the computational effort. Gorazd Karer et al. [7] used an MPC for nonlinear hybrid systems with discrete inputs. They proposed a hybrid fuzzy modeling approach to provide a model for the MPC. They applied their proposed scheme on a batch reactor system to verify it and provided a comparison between two MPCs based on a hybrid linear model and a hybrid fuzzy model. Heidarinejad et al. developed an MPC via Lyapunov based techniques for a wide range of nonlinear process systems [11]. Their MPC optimizes closed-loop performance by consideration of general economical aspects. In contrast with conventional MPC which are necessarily based on steady-state, they proposed a cost function based on the desired

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Nomenclature

MPC	Model predictive control
RMPC	Robust model predictive control
LBMPC	Learning-based model predictive control
PWA	Piecewise affine
OOP	Open-loop optimization problem
BA	Bees algorithm
n	Number of scout bees
m	Number of selected sites out of visited sites
e	Number of best sites out of selected sites
nep	Number of recruited bees for best sites
nsp	Number of recruited bees for the other selected sites
ngh	Initial size of patches
x	State variable
y	Output
u	Input signal
u_c	Continuous input signal
u_d	Discrete input signal
$\hat{n}$	Positive integer number
T_s	Sampling times
f	Cost function
hp	Prediction horizon
Q	Liquid flow
V	Switching valve
h	Liquid level
A	The cross-sectional area of each tanks
a_z	Flow correction term
S	Cross-section of valve
g	Gravity constant
h_v	Height of valve
w	Weight of the cost function
x_r	Reference signal
MLD	Mixed logical dynamical
HYSDEL	Hybrid system description language
GLPK	GNU linear programming kit

economic considerations. Another type of MPC is proposed by Ling et al. [12]. In their paper, control variables are moved asynchronously which is in contrast with most multi-input multi-output (MIMO) control schemes. They focused their effort to reduce the computational complexity of applying an MPC to complex systems with fast response times. Aswani et al. [14] presented a learning-based MPC (LBMPC) scheme to guaranty robustness whilst using statistical identification tools to obtain richer models of the system in order to improve performance. They used two models of the system, one was an approximate model with bounded uncertainty and the other one was an updated by statistical methods, in order to improve performance and ensure robustness. Finally, in [15], Lazar extend the MPC approach in order to control certain classes of hybrid systems. He discussed the stabilization and the robust stabilization of these systems. The proposed MPC utilized piecewise affine (PWA) model of hybrid systems. He concentrated his effort on PWA modeling approach and developed an algorithm for calculating low complexity piecewise polyhedral invariant sets.

As discussed, researchers still work on the MPCs in order to increase their optimality, robustness and applicability, and to decrease their computational effort. Therefore, it is a significant open challenge to study simple, general and systematic methods with decreased computational costs while increasing the optimality and convergence.

Different MPCs exploit different algorithms in order to solve the OOP whilst using a model of system to predict future behavior of the system and adjust the output(s) of the system without breaching the constraints. In this paper an algorithm is proposed for solving the OOP for a class of autonomous nonlinear systems (The definition of autonomous system for a nonlinear system is the same as the definition of time-invariant system for a linear system. This definition is based on [17].) without delay which have continuous and discrete inputs. The proposed algorithm is specifically designed for controlling systems with both continuous and discrete inputs. Within the proposed algorithm many different intelligent algorithms can be used for solving the OOP such as Bees algorithm, Ant algorithm and Genetic algorithm, but due to the main hurdle in any model predictive control is to decrease computational costs while increasing the optimality and convergence, in this paper a bees algorithm (BA) is used because of its short convergence time and high computation speed. This paper utilizes a bees algorithm based on foraging behavior of honey bees to solve the OOP. The controller tries to minimize a predefined cost function by manipulating the discrete and continuous inputs. First the algorithm is introduced with unit prediction horizon. Then because the unit prediction horizon may be not reliable for some systems and in order to improve the results, the general form of the algorithm is proposed to extend the prediction horizon. The main goal of the proposed algorithm is to provide a simple systematic procedure for designing an MPC whilst decreasing convergence time and computational effort. Therefore, the proposed method provides the advantages of reduction in computation time, premium convergence toward desired values, ability of control management, generality of the method, using nonlinear model and simplicity of cost function. To provide a reference for evaluation of the algorithm a typical configuration of three tank system is used as a case study. Notice that using a highly nonlinear system such as a three tank system is not affect generality of the proposed algorithm and its applicability to the linear systems. However, it may be more reasonable to use well-developed traditional control approaches with low implementation cost for linear systems. Also in order to show advantages of the proposed algorithm, results of the proposed algorithm are compared with a well-developed conventional optimization method for the three tank system [18]. The main difficulty with this configuration of three tank system is that the system is not only controlled via continuous inputs but also controlled via discrete valves with on or off positions. Different modes may appear based on the positions of discrete valves. In this system the main goal is to provide a constant output flow from one of the tanks, but due to the type of valves which are on/off valves, output flow has to be controlled through the liquid level in the tank. Comparisons between the proposed algorithm and a conventional MPC show advantages such as simplicity, and efficiency. In addition, it is shown that using the bees algorithm decreases computation time and convergence time in contrast with the conventional optimization method which uses the hybrid model of the three tank system [18].

The rest of the paper is organized as follows. In Section 2, a short introduction on bees algorithm is first provided and then an algorithm for designing an MPC based on the bees algorithm is proposed. Afterwards the general form of the algorithm is introduced for extending the prediction horizon and improving the results. In Section 3, a three tank system is introduced as a case study and the mathematical model of the system is described. The application of the proposed algorithm to the three tank system is provided in Section 4. In addition, in this section the results of simulations and comparisons with another well-developed conventional optimization method are presented. Finally, concluding remarks are drawn in Section 5.