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A novel hybrid bacteria-chemotaxis spiral-dynamic algorithm with application to modelling of flexible systems

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ABSTRACT

This paper presents a novel hybrid optimisation algorithm namely HBCSD, which synergises a bacterial foraging algorithm (BFA) and spiral dynamics algorithm (SDA). The main objective of this strategy is to develop an algorithm that is capable to reach a global optimum point at the end of the final solution with a faster convergence speed compared to its predecessor algorithms. The BFA is incorporated into the algorithm to act as a global search or exploration phase. The solutions from the exploration phase then feed into SDA, which acts as a local search or exploitation phase. The proposed algorithm is used in dynamic modelling of two types of flexible systems, namely a flexible robot manipulator and a twin rotor system. The results obtained show that the proposed algorithm outperforms its predecessor algorithms in terms of fitness accuracy, convergence speed, and time-domain and frequency-domain dynamic characterisation of the two flexible systems.

1. Introduction

This section presents a general overview of metaheuristic algorithms and a general description of the two types of metaheuristic algorithms, including their characteristic features considered in this study. Moreover, a brief description of two types of flexible systems and their status in the current research in the context of modelling and controller design is given. Finally, an overview of the application of various types of optimisation algorithms in modelling of flexible systems is presented.

1.1. *Flexible systems*

The research on flexible systems is increasingly gaining attention from researchers worldwide. The application of such system can be extensively found in various sectors such as in robotics (Gharooni et al., 2001), avionics (Hu, 2009), etc. This is due to the numerous advantages they offer compared to their rigid body counterparts. Two types of commonly used flexible manoeuvring system, namely flexible robot manipulator and twin rotor system (TRS) are considered in this work.

Flexible robot manipulators are used in the manufacturing industry as a tool in the production process. A single-link flexible manipulator is considered in this work. This is a single-input multi-output system comprising rigid and flexible dynamics. Electromechanical actuator at the hub of the system produces rotational motion of rigid body while a flexible beam joining the rigid body and payload produces vibrational motion at the end point of the system. The natural vibrational behaviour of the system poses control challenge in applications where positional accuracy is required. However, the flexible structure of the system exhibits a lot of benefits over its rigid counterpart. Unlike a rigid manipulator, it is lighter in weight, has smaller actuator, better mobility, consumes less power, is less expensive, operates cost-efficiently, has higher payload to robot weight ratio and offers more safety to the user (Ostergaard (2012); Tokhi et al., 2000).

The TRS used in this work is a laboratory scale flexible manoeuvring system, which mimics a real helicopter in hovering mode. In real world, the application of such a system is mostly found as air transportation. It is considered as a very effective air vehicle as it is capable to take off and land in the vertical direction, which requires less space compared to fixed wing aircraft, rotate its body 360° easily in hovering mode, fly at low altitude (Raptis et al., 2012). The body construction of the system is very unique and complex. It has vertical and horizontal channels to initiate motion in vertical and horizontal directions respectively. Moreover, interaction between both channels introduces coupling effect and hence produces nonlinearity in its dynamic behaviour. While in hovering mode, motion-induced oscillation causes the system to fluctuate and lose stability. Therefore, an efficient control system is required to operate the system effectively.

Modelling and control of flexible systems are challenging tasks. Their vibrational behaviour and nonlinear characteristics make the modelling of such systems a challenge and lead to very complex

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mathematical models. Through conventional modelling approaches such as partial differential equation (Azad, 1994), finite-difference, finite-element methods (Tokhi and Azad, 1995; Tokhi and Mohamed, 1999), to get a very precise model, many parameters should be taken into account and in many cases, certain assumptions have to be made to simplify the derivation of equation of motion, thus reducing the accuracy of the derived model. From a model-based control point of view, an accurate model of the system is very crucial since the effectiveness of a designed controller is based on the derived model. System identification is an alternative approach to acquire dynamic model of the flexible system based on input–output data from the actual system. The availability of optimisation algorithms and powerful computing technology make this method easy to implement, reliable and more importantly can result in highly accurate models. Linear parametric approach is one of various techniques in system identification to estimate a linear model of a system (Ljung, 1999). In this method, a set of unknown parameters in a predefined structure must be identified. The parameters are set of zeros and poles if the structure is represented by a transfer function or a set of coefficients for a differential equation. The applications of this approach in the engineering field have extensively been reported in the literature (Niño et al., 2007; Tavakolpour et al., 2010). Moreover, the implementation of identification for unknown parameters of a dynamic model of a system in linear parametric modelling can be easily realised using metaheuristic algorithms.

1.2. Overview of the application of optimisation algorithms to modelling of flexible systems

The application of various optimisation algorithms to optimally determine dynamic model of predefined linear and non-linear structures for a real system through system identification approach has been extensively found in the literature. This section gives an overview of the application of the algorithm in the modelling of the flexible robot manipulator and the TRS.

Rovner and Cannon (1987) and Fujimori et al. (1995) employed recursive least squares (RLS) to optimise the dynamic model of a flexible manipulator system. Yurkovich et al. (1990) proposed an exponential data weighted RLS in comparison to original RLS algorithm to optimise autoregressive-moving-average (ARMA) model. Shaheed and Tokhi (2002) conducted a study comparing least mean squares (LMS), RLS and genetic algorithm (GA) to optimise parameters of an autoregressive-moving-average model with exogenous inputs (ARMAX) model of flexible manipulator. It was shown that the GA could produce better results than the LMS but it needed more time to complete the whole optimisation process compared to the other two contestants. Liu and Sun (2001) applied observability range space extraction algorithm to optimise a dynamic model for a single link flexible manipulator. Alam and Tokhi (2007a) employed particle swarm optimisation (PSO) to optimise the parameters of an ARMA model structure of the flexible manipulator. Md. Zain et al. (2009a,b) carried out comparative assessment of RLS, GA and hybrid GA–RLS in the optimisation of ARMA model of a flexible manipulator. The results show that the hybrid type algorithm produced better dynamic model compared to the original algorithms but at the expense of longer computation time. Supriyono and Tokhi (2012) employed adaptive and original bacterial foraging algorithm (BFA) to optimise autoregressive with exogenous inputs (ARX) dynamic model of structure of the flexible manipulator. The results indicated that the adaptive approach produced more adequate dynamic model for the system but the total computation time for the optimisation process was similar. Yatim et al. (2012) performed a study comparing conventional least square and GA to optimise a linearised model of single link manipulator system which was developed based on finite difference method. It was found that the conventional least square predicted better model for a linearised system. In another work, the authors compared the PSO with RLS to optimise the same system and it was found that the PSO performed better than the conventional RLS algorithm (Yatim et al., 2013).

For the TRS, on the other hand, the utilisation of the system identification toolbox of Matlab to optimise an ARMAX model was presented by Ahmad et al. (2001). Aldebrez et al. (2004) employed RLS algorithm to optimise a multi-layer perceptron neural network model. Mat Darus et al. (2004) conducted a study on comparing the performances of GA and conventional RLS to optimise an ARMAX model and it was found that the GA predicted better model as compared to the RLS. Alam and Tokhi (2007b) performed a comparative assessment of GA and PSO to approximate a linear model for one and two degrees-of-freedom (DOF) TRS. The results showed that the PSO had better accuracy and shorter computation time than the GA. Subudhi and Jena (2009) hybridised the GA, PSO and differential evolutionary (DE) algorithm with back-propagation (BP) algorithm to optimise a neural network model for one DOF around a pitch axis and the hybrid DE was found with fastest convergence speed. A comparative study was performed by Toha and Tokhi (2010) where the RLS, real-coded GA and PSO with spread-factor were used to determine parameters of ARMA model. The results indicated that the PSO with spread-factor outperformed the other two algorithms. Omar et al. (2011) applied the hybrid RLS–BP to optimise an adaptive neuro-fuzzy model for the twin-rotor motion in the vertical plane or pitch motion. Toha et al. (2012) employed ant colony algorithm to optimise ARX model of the TRS and the results showed that the estimated model was adequate to represent system. It is noted from the above that the performance of metaheuristic algorithm in dealing with the modelling issue of a real system is better than the heuristic or other conventional type algorithms.

1.3. Metaheuristic algorithms

Metaheuristic algorithms play an important role and are considered as efficient optimisation tools in solving real world problems in various fields (Neri and Cotta, 2012; Zang et al., 2010). A metaheuristic algorithm is a higher level optimisation algorithm comprising a heuristic approach and iterative process in which the strategy is generally inspired from natural phenomena. Alternatively, metaheuristic can be defined as a process that is iteratively generated to guide a subordinate heuristic by combining intelligently various techniques for globally exploring and locally exploiting a search area and utilising learning strategies to structure information in order to efficiently find an optimum solution (Osman and Laporte, 1996). The ease of implementation, ability to solve real world problems in various applications and the capability of producing an optimum and a reliable solution are the advantages and among the reasons they have been continuously received attention from researchers around the world. BFA is a popular and well-known metaheuristic type algorithm while spiral dynamics algorithm (SDA) is a newly developed metaheuristic algorithm that has similar advantages and potential to solve real world problems efficiently. Nevertheless, these two algorithms have limitations and drawbacks which are discussed in the following subsections.

1.3.1. Bacterial foraging algorithm

BFA is a metaheuristic algorithm introduced by Passino (2002) and it was developed based on the adaptation of foraging strategy of living micro-organism in human intestines, namely Escherichia Coli bacteria. The algorithm consists of three main phases, namely chemotaxis, reproduction, and elimination-dispersal.